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Industrial Environmental Research
Laboratory
Research Triangle Park NC 27711

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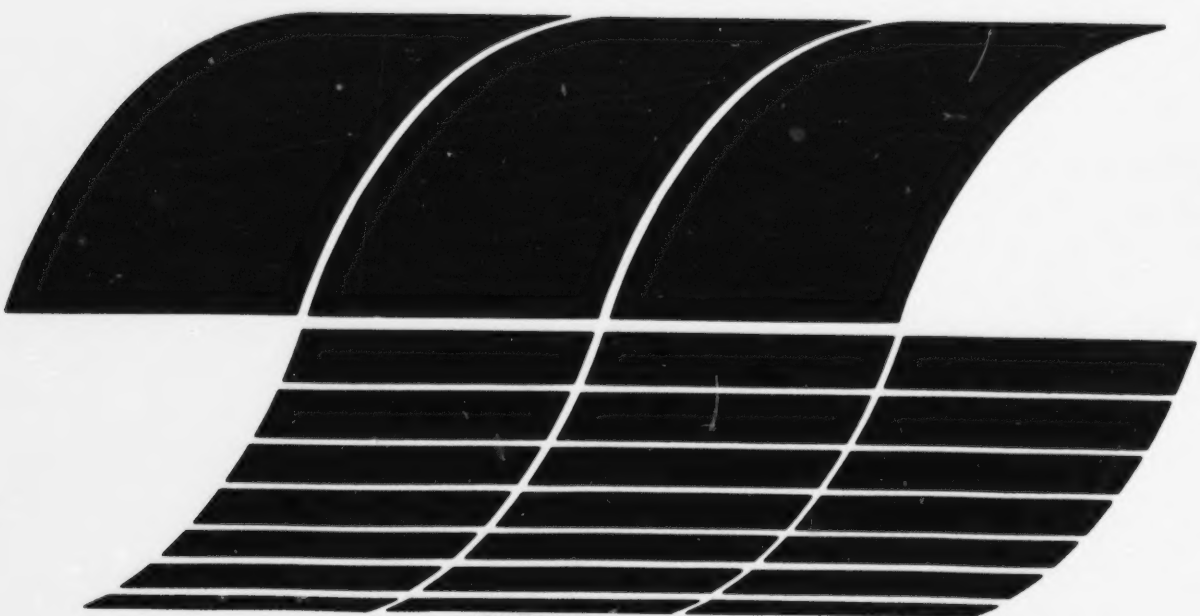
September 1978

# Magnetite Recovery in Coal Washing by High Gradient Magnetic Separation

## Interagency Energy/Environment R&D Program Report



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# Magnetite Recovery in Coal Washing by High Gradient Magnetic Separation

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Division of Solid Fuel Mining and Preparation
Pittsburgh, PA 15213

# MAGNETITE RECOVERY IN COAL WASHING BY HIGH GRADIENT MAGNETIC SEPARATION

Final Report

October 1977

Contract ET-76-C-01-8887

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## ABSTRACT

A research program at the Francis Bitter National Magnet Laboratory has demonstrated successful recovery of magnetite from mixtures of magnetite and coal — like those found in a coal-washing circuit — by High Gradient Magnetic Separation. High values of magnetite recovery were achieved at reasonably high material throughput rates with little coal found reporting to the magnetics. A single-stage separator incorporating a new matrix design was used at rates up to 4.4 tons of solids per hour per square foot of matrix cross-section (300 gpm/ft$^2$). At this throughput rate, more than 99% of the magnetite was trapped along with less than 5% of the coal. Magnetic field values no higher than 6 kilogauss were used to achieve these results, a value well within the range of present commercial magnet designs.

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## INTRODUCTION AND SUMMARY

The objective of this research program is to apply High Gradient Magnetic Separation (HGMS) to the problem of the recovery of fine magnetite from dense-medium circuits in coal preparation plants. Fine magnetite mixed into a water suspension is commonly used in coal preparation to create a pseudo-specific gravity great enough to effect separations between coal and associated impurities. The magnetite must not only be reclaimed but must also be cleaned to prevent coal and impurities from building up in the washing circuit. The reclaimed coal fines have economic value. Studies have been made of the performance of dense-medium cyclones treating coals down to 100 mesh at the Bureau of Mines. Sharp separations have been achieved by reducing the top size of the feed to the cyclone. Such recent advances in the cleaning of finer sizes of coal required that entire coal-magnetite streams, which are normally run over drain and rinse screens for separation of a large portion of the magnetite, be fed directly to magnetic separators. The capacity of conventional drum-type separators is such that multiple units are required to handle the flow. HGMS may afford the same capability in fewer separating units.

High gradient magnetic separators are either of the batch or continuous type. The batch separator consists of a canister of appropriate size, containing the matrix, enclosed by a solenoid which produces the required magnetic field. Commercial units of this type capable of handling 60 tons of solids per hour have been made for the kaolin industry. In our laboratory we have several small experimental separators which can be used in a variety of magnets at fields up to 100 kG. For handling magnetite, however, fields of the order of 1-20 kG are adequate, and can be realized with good conventional magnet technology using iron bound electromagnets.

Continuous separators of the high gradient type have been built on an experimental basis. We have used one such unit, the prototype Carousel Separator which can handle about 3 tons (dry wt.) of feed per hour. This device has been used to demonstrate the applicability of high gradient

separation to the beneficiation of oxidized taconite in a cooperative program with the Hanna Mining Company under the sponsorship of the RANN Division of the National Science Foundation. Other pilot-plant size continuous separators have been built with matrix size up to 15 feet in diameter and capacities of several hundreds of tons of feed per hour. Figure 1 is a schematic of a Carousel Separator and Fig. 2 shows the prototype set up as a pilot plant device in an iron ore laboratory.

Batch separators are practical and are used on a commercial scale where the magnetics fraction to be removed from the slurry amounts to only a few percent of the total throughput. The matrix is periodically backwashed to remove the magnetics from the matrix. During the backwash interval the slurry is either diverted to a surge tank or to another magnetic separator.

If the magnetics fraction is high, a continuous separator may be called for. In the continuous separator the matrix is in annular form, (resembling the carousel in the carousel slide projector) and rotates in and out of the magnetic field. The washing is done on that portion of the matrix which is outside of the field. The magnetics are then continuously collected and continuously washed.

The throughput capacity of HGMS separators which have been used at this laboratory is as high as 500 gpm/ft$^2$. This flow was used to strip kaolin clay from magnetite following agglomeration of these materials in water purification work. By contrast, multiple drums have possible feed rates of 50-100 gpm/ft of width. There is a definite economic advantage of higher flow rates in reducing the machine size necessary for use in a coal washing plant.

Drum separators are affected by the amount of magnetics in the slurry.[1] The recovery decreases in dilute slurries — an effect not seen in high gradient separators. Also they are limited to 20% solids or less in the feed and 60-70 gpm/ft of drum width if the non-magnetics content is required to be less than 10%. This corresponds to a limit of 2.9 tons per

hour per foot of drum width. For a 30" drum this is 1.15 tph/ft width per foot diameter.

Two hundred twelve experimental runs were made in this study using an Upper Freeport coal (9 x 100 mesh) slurried in water together with (96% -325 mesh) commercial magnetite. A new matrix design, which was used for all of the work described in detail in this report, was developed as part of this project. Single passes were made through the separator with a feed equivalent to the feed to a heavy-medium cyclone. Some separations were performed on simulated cyclone overflow and underflow streams, and both the coal and magnetite were fed alone to the separator to determine performance characteristics.

The throughput rates in this study varied from 1 to 4.4 tph/$ft^2$ of matrix with the best results at the highest rates. The least amounts of non-magnetics in the magnetic concentrate occurred at the highest throughput values and high levels of magnetite recovery were maintained.

Typical figures in a series of runs in which the magnetic field was varied from 2 to 6 kilogauss were 99 to 100% magnetics recovery with an average value of 4.8% of non-magnetics in the magnetics. In these runs the flow rate was roughly 300 gpm/$ft^2$ and the feed was a slurry with a solids density of 15.6%. The throughput average value was 4.1 tph/$ft^2$ of matrix calculated from the total solids passed in the time taken to collect the total non-magnetic fraction of the slurry. This fraction included some extra water following the slurry. This was done to maintain a head for constant flow. If the time was known for the slurry alone, the throughput calculation would result in a higher figure. In further work larger samples will be used and this throughput value obtained.

The head mentioned above was only a few inches above the matrix. Higher heads will be used in the future which will result in higher throughput and flow rate values. Continuous rotating HGMS separators have separate slurry and wash water flows so that, in practice, if these were used for this application, the throughput would be exactly determined by the slurry flow rate.

One possible application of HGMS in coal beneficiation would be as a secondary magnetic separator following a primary drum for magnetite recovery. Since HGMS is particularly well suited to the recovery of particles with sizes ranging down to below 1 micron, the magnetite slimes and fine particles that cannot be recovered by drums would be retained in the High Gradient Separator. While a magnetic field strength of 5 or 10 kilogauss or more is required for the capture of paramagnetic particles such as those found in oxidized taconite iron ores, previous work by us has shown that 1 kG is sufficient to trap 100% of laboratory samples of magnetite. The size range of these samples was 0.6-2.5 microns.[2]

An alternative application would be the use of HGMS as a primary magnetite separator. Used this way it would replace drums altogether. The amount of magnetite retained would be much greater than it would be in its use as a secondary separator but it has been shown that HGMS separators can retain 80% or more of the solids in a 40% density stream of iron ore without plugging. Separation was achieved even at a high recovery level (96% Fe recovery). It is indicated, then, that high recovery of magnetite would be possible with the required cleaning even for the wider range of particle sizes found in the feed to a primary drum.

It remains to be seen whether a batch or continuous separator would be desirable in an industrial magnetite separation process. The batch separators would be simpler and cheaper and if the wash water containing the magnetite is dilute enough they would be practicable. In this introductory study we used batch separators. Past experience in iron ore processing, with the Carousel Separator, has shown that it is possible to correlate batch separator performance with Carousel Separator performance under corresponding conditions of magnetic field and flow rate.

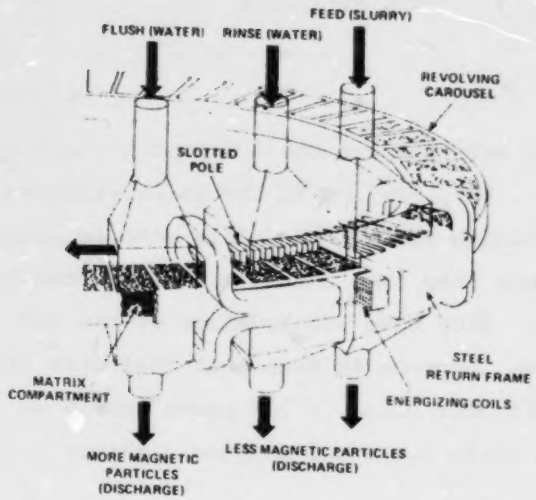



Figure 1. Schematic of continuous Carousel High Gradient Magnetic Separator.

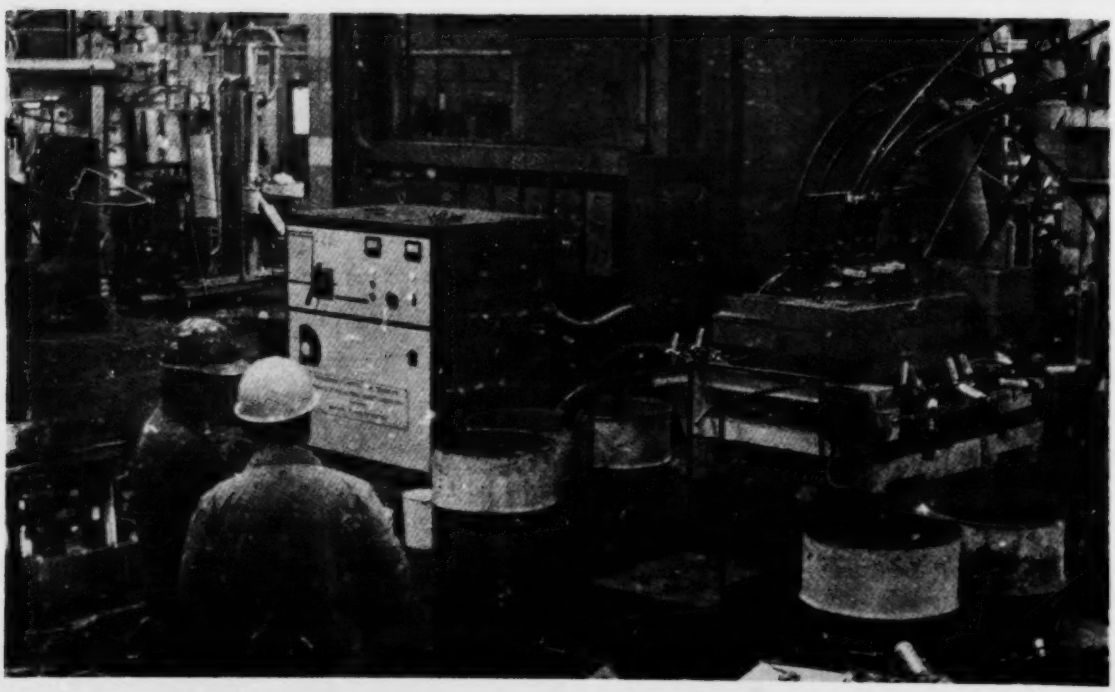


Figure 2. The Carousel High Gradient Magnetic Separator with its power supply at a mining company research laboratory. Feed and wash pipes enter the Carousel at the top.

## FEED MATERIALS

### Coal

The feed coal for this project consisted of a blend of two Upper Freeport coals (Indiana Co., Pa), blended in the ratio expected to be used at the Homer City Coal Cleaning Plant. The coals were collected over several hours to avoid variations from such causes as differences in mining machine, sharpness of bits, etc. They were put together by the R&P Coal Co. in the ratio of 575-600 pounds Lucerne #6 Mine coal (Helvetia Mining Co.) and 275 pounds Helen Mining Co. coal. A 200-pound sample of 2 mm x 100 mesh (149 μ) was made from these coals and shipped directly to us on September 20, 1976.

A screen analysis was made by Eastern Associated Coal Corp. Research Laboratory in Everett, Massachusetts and is shown in Table 1. The largest weight fraction is between 14 and 28 mesh (1.19 mm x 595 μ) (Tyler) which means that the separation process and the matrix design must be such that particles this large can pass the matrix easily. Of course, the same matrix must trap magnetite which contains particles even smaller than 1 micron.

A 20-pound sample of the coal was split at 1.30 specific gravity by Eastern for use as discussed later. The results of this split were 48.4% float and 51.6% sink. Analyses of the feed coal were performed to determine percent ash, % moisture, % iron, and % Davis Tube magnetics. Results are shown in Table 2. The moisture was taken on several samples by the standard ASTM method. All other analyses are on an as-received basis.

Magnetics were measured by us using a magnetometric method and Davis Tube magnetics were measured by Mr. Richard Hucko at the Bureau of Mines and the value is exactly zero for the feed coal.

TABLE I

Feed Coal Size Analysis

| Screen Size | Wt. % |
|---|---|
| 1/8" x 14 mesh | 21.0 |
| 14 x 28 " | 34.6 |
| 28 x 48 " | 24.6 |
| 48 x 100 " | 16.9 |
| 100 x 200 " | 1.5 |
| - 200 " | 1.4 |

TABLE 2

Feed Coal Analysis

| | FLOAT* % | SINK* % | MOISTURE % | ASH % | IRON % | MAGNETICS MAGNETOMETER % | (DAVIS TUBE) |
|---|---|---|---|---|---|---|---|
| As Received | 48.4 | 51.6 | 1.3 | 13.2 | 2.33 | 0.0 | (0.0) |
| Float Product* | | | | 2.4 | 0.28 | | |
| Sink Product* | | | | 29.6 | 5.0 | | |

*Specific Gravity = 1.30

Magnetics measurement is one way of locating magnetite lost in the non-mags stream and, as will be seen in the results section, this loss can be very low. We believe that the Davis Tube does not necessarily indicate all of the magnetics which might be trapped in a HGMS device, so a more sensitive magnetometric method was devised under this contract.

The feed coal contained no magnetics discernible by either of these methods. However, the HGMS results on the feed coal at two flow rates and two magnetic field values showed that some material was trapped by the matrix. The results are shown in Table 3 where, for full flow, about one-third of a percent by weight was trapped (Runs 201, 202). The amount was essentially independent of field and therefore is considered to be caused by mechanical trapping.

At the fast flow rate, material trapped magnetically would be the more strongly magnetic particles or larger ones with a large magnetic moment. The higher field should result in trapping some smaller or more weakly magnetic particles <u>if</u> the trapping were caused by magnetic forces. But there is no increase between 3 and 6 kG.

At the slower flow rate a small increase is seen in magnetics (from 2.9 to 3.5 percent weight) but there is some material balance error beyond the average for these runs so that little can be concluded except that we see little or no field effect and, hence, attribute this trapping to mechanical causes. This is not strange to those with experience in HGMS. In fact, the low level of material trapping when coal alone is fed to the separator is important because it indicates the ability of the separator to successfully pass large particles, a necessary but not sufficient condition for success in making the coal-magnetite separation. The slower flow runs were made to provide information of this kind, even though faster flow rates are more desirable and were generally used in our tests.

TABLE 3

Magnetic Separation of Feed Coal

| RUN | MAGNETIC FIELD (kG) | VELOCITY (cm/sec) | SAMPLE | % WEIGHT non-mags | % WEIGHT mags | % IRON non-mags | % IRON mags | FLOW RESTRICTOR (gal/min) |
|---|---|---|---|---|---|---|---|---|
| 199 | 3.0 | 32.6 | 300.00 gm coal (feed)<br>1305 ml $H_2O$<br>18.7% solids by weight | 97.1 | 2.9 | | | 3 |
| 200 | 6.0 | 32.5 | SAME | 96.5 | 3.5 | 2.01 | 6.71 | 3 |
| 201 | 3.0 | 117.4 | SAME | 99.7 | 0.3 | | | - |
| 202 | 6.0 | 148.4 | SAME | 99.7 | 0.3 | | | - |

Figure 3 is a plot of the percent weight capture in these runs. The straight lines drawn allow an estimate to be made of the capture due to coal alone at several fields if one dares to interpolate. We should note, however, that the capture characteristics of the magnetite differ substantially from runs for which it is the sole feed material and those in which it is mixed with coal. One might expect the same to be true for the impurities in the coal, so we cannot place much emphasis on this attempt to keep track of materials that pass through the separator. We will make limited use of this information later on, however.

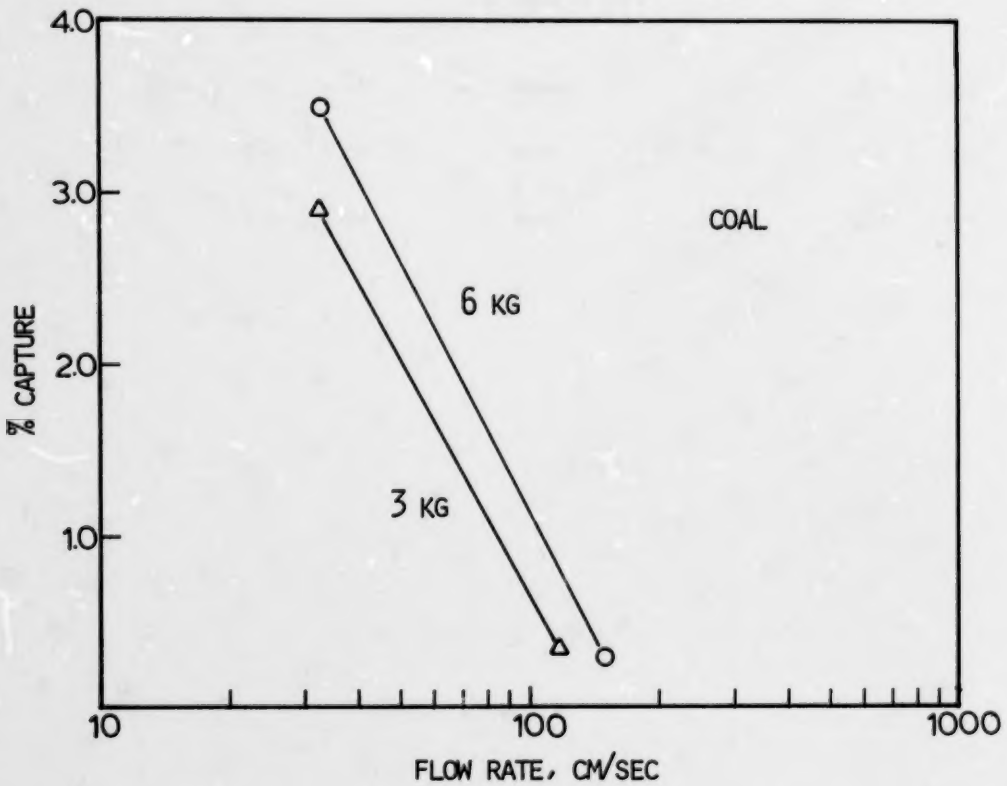



Figure 3. Magnetics capture (%) from the feed coal as a function of flow rate. Feed = 300 gms.

Magnetite

The magnetite for this project was obtained from the Reiss-Viking Corp. in Bristol, Tennessee. The first sample received was 40 pounds of Grade E (96-97 % -325 mesh, 90 % -30μ, 36 % -5μ) and the second was 100 pounds of the same material. This grade of magnetite is required for washing coal reduced to 100 mesh and is the grade expected to be used at Homer City. Only one brand of magnetite was used on the advice of Bureau of Mines personnel. The magnetite is mined, crushed, and ball mill ground until the 325 mesh requirement is met. It is dried by the supplier. This grade is stated to have 91% magnetics by Davis Tube.

We include a table of magnetite grades and typical size composition of these (Table 4). This was provided by Mr. A.W. Deurbrouck of the Bureau of Mines. The largest fraction is between 10 and 20μ in particle size (29.5%) with the 5-10μ range close behind (28.5%). Along with this, Table 5 shows a typical size analysis by weight from our HIAC particle size analyzer. This shows a similar distribution except that the largest fractions are in the 8-15μ and 5-8μ range. This indicates more fine particles than the screen analysis. The density, assumed shape, and method of determining weight fraction may differ among types of analyses and account for variations between distributions.

Other analyses of the Reiss-Viking (R-V) magnetite included iron, ash, sulfur, float-sink, magnetometric and photographic. In addition, a number of runs were made on the HGMS with various matrices and conditions to characterize the behavior of the magnetite before it was used to make feed samples. These analyses are summarized in Table 6. It is interesting to calculate the weight of the ash if we assume the simplest conversion of $Fe_3O_4$ to $Fe_2O_3$ according to the reaction

$$2\ Fe_3O_4 + \frac{1}{2}\ O_2 \longrightarrow 3\ Fe_2O_3$$

the weight ratio would be 1.035, close to our experimental value of 1.024 (1% difference). This calculation assumes, of course, that the material which is not $Fe_3O_4$ does not change weight and we do not know that.

TABLE 4

Magnetite Grades

| PARTICLE SIZE PERCENT MINUS 325 MESH | FOOTE MINERAL CO. | MINERAL MILL CO. | VIKING CORP. |
|---|---|---|---|
| 55 to 70 | A | 2 | 55/70 |
| 90 | B | 1 | 90 |
| 96 | E | 6 | 96 |
| 98 | F | - | 989 |

Average Size Composition of Magnetite Used in Dense-Medium Separators

| SIZE COMPOSITION, MICRONS | COMPANY X | | COMPANY Y | | COMPANY Z | |
|---|---|---|---|---|---|---|
| | GRADE B | GRADE E | GRADE B | GRADE E | GRADE B | GRADE E |
| | PERCENT PASSING | | | | | |
| 90 | 97.0 | 98.0 | 99.0 | 100.0 | 99.0 | 99.5 |
| 74 = (200 mesh) | 95.0 | 97.5 | 98.0 | 100.0 | 97.0 | 99.5 |
| 60 | 92.5 | 97.5 | 97.0 | 100.0 | 94.5 | 99.0 |
| 44 = (325 mesh) | 87.5 | 96.0 | 90.0 | 97.5 | 85.0 | 96.5 |
| 30 | 74.0 | 84.5 | 68.0 | 86.5 | 67.5 | 84.0 |
| 20 | 62.0 | 74.5 | 53.5 | 66.5 | 53.5 | 69.0 |
| 10 | 36.0 | 44.5 | 32.5 | 37.5 | 32.0 | 39.5 |
| 5 | 8.0 | 12.0 | 7.5 | 11.0 | 7.0 | 11.0 |

TABLE 5

Magnetite Size Distribution, HIAC Analysis

| PARTICLE SIZE, μ | WEIGHT % BELOW STATED SIZE |
|---|---|
| 60 | 100 |
| 20 | 91.6 |
| 15 | 88.7 |
| 8 | 58.2 |
| 5 | 30.0 |
| 3 | 7.0 |

TABLE 6

Analysis of Reiss-Viking Magnetite

| ANALYSIS | % BY WEIGHT |
|---|---|
| Iron | 63.3 |
| Ash | 102.4 (± 0.1) |
| Sulfur | 0.18 |
| Float (Sp. Grav. = 1.30) | 0.0 |
| Sink (Sp. Grav. = 1.30) | 100.0 |
| Magnetics (Davis Tube) | 90-91 |
| Retention (HGMS) | 96 |

In our magnetometric analysis we took the magnetite as a standard at 100% magnetics and in the HGMS we repeatedly collected about 96% magnetics when we ran the magnetite alone at sufficient field (2-6 kG) and so believe the $Fe_3O_4$ content to be higher than that indicated by chemical analysis.

The results of the HGMS Runs 101-110 using a new double screen matrix are shown in Table 7 and in Fig. 4. Note the concentration of magnetics from 91% in the feed to 96% in the magnetic product.

Further, the Reiss-Viking magnetite was subjected to a Mossbauer analysis to determine its molecular structure. This was performed by Dr. Richard Frankel of this laboratory and the results are straightforward. The spectrum could be read to within 5%. All of the iron in this sample appeared to reside in sites characteristic of the $Fe_3O_4$ structure, so that at least 95% of the iron is contained in the $Fe_3O_4$ form to within experimental error.

Table 8 and Fig. 5 show the results of loading tests on the double screen matrix with magnetite alone. The sample weights range from 75 to 600 gms. The first six runs in the table cover this range and show that recovery is independent of loading. A curve has been drawn for these points which represent runs in which a dispersant was used. The next two runs (150 and 151) were done at 25.6% solids density, higher than the previous series except for the last point (113), and still there is no apparent loading effect. Repeating these two runs, however, without the dispersant (153, 154) shows a higher capture for the high loading point and about the same for the 300 gm sample as with the dispersant.

Looking at the percent iron in the magnetic fraction and the Davis Tube data, these do not differ from the magnetite itself by very much except for the Davis Tube readings which are higher than the 91% for the feed. So, the separator concentrates the magnetite and does so independently of the loading in this range.

TABLE 7

HGMS Results With Reiss-Viking Magnetite

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | SAMPLE | % WEIGHT NON-MAGS | % WEIGHT MAGS | % MAGNETICS IN MAGS (DAVIS TUBE) |
|---|---|---|---|---|---|---|
| 103 | 0.2 | 1.8 | 150.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant<br>10.3% by weight solids | 91.7 | 8.3 | |
| 108 | 0.2 | 1.2 | SAME | 88.9 | 11.1 | |
| 104 | 0.5 | 2.2 | SAME | 43.0 | 57.0 | (96.6) |
| 109 | 0.5 | 1.1 | SAME | 40.9 | 59.1 | |
| 105 | 1.0 | 1.7 | SAME | 8.3 | 91.7 | (96.2) |
| 101 | 2.0 | 2.5 | SAME | 4.8 | 95.2 | |
| 106 | 2.0 | 1.8 | SAME | 5.3 | 94.7 | (95.1) |
| 102 | 3.0 | 3.2 | SAME | 4.5 | 95.5 | |
| 107 | 3.0 | 3.0 | SAME | 5.0 | 95.0 | (95.6) |
| 110 | 3.0 | 1.5 | 75.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant<br>5.4% solids by weight | 5.7 | 94.3 | (96.4) |

TABLE 8

Effect of Loading Matrix With Reiss-Viking Magnetite

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | SAMPLE | % SOLIDS (by weight) | % WEIGHT non-mags | % WEIGHT mags | % MAGNETICS non-mags mags (Davis Tube) | % IRON non-mags | % IRON mags | % $Fe_3O_4$* (calculated) Mags |
|---|---|---|---|---|---|---|---|---|---|---|
| 102 | 3.0 | 3.2 | 150.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant | 10.3 | 4.5 | 95.5 | | | | |
| 107 | 3.0 | 3.0 | SAME | 10.3 | 5.0 | 95.0 | (95.6) | | | |
| 110 | 3.0 | 1.5 | 75.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant | 5.4 | 5.7 | 94.3 | (96.4) | 21.57 | 65.37 | 90.3 |
| 111 | 3.0 | 2.3 | 100.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant | 7.1 | 5.5 | 94.5 | | 20.24 | 65.29 | 90.2 |
| 112 | 3.0 | 3.6 | 300 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant | 18.7 | 4.4 | 95.6 | | 21.62 | 64.81 | 89.6 |
| 113 | 3.0 | 6.4 | 600.00 gm R-V magnetite<br>1305 ml $H_2O$<br>20 ml dispersant | 31.5 | 2.6 | 97.4 | | 15.82 | 64.20 | 88.7 |
| 150 | 3.0 | 2.3 | 300.00 gm R-V magnetite<br>870 ml $H_2O$<br>20 ml dispersant | 25.6 | 2.7 | 97.3 | | | | |
| 151 | 3.0 | 0.3 | 600.00 gm R-V magnetite<br>1740 ml $H_2O$<br>40 ml dispersant | 25.6 | 2.0 | 98.0 | | | | |
| 153 | 3.0 | 2.3 | 300.00 gm R-V magnetite<br>870 ml $H_2O$ | 25.6 | 2.8 | 97.2 | (93.0) | | | |
| 154 | 3.0 | 0.2 | 600.00 gm R-V magnetite<br>1740 ml $H_2O$ | 25.6 | 0.9 | 99.1 | | | | |

*$Fe_3O_4$ = 72.36% Fe

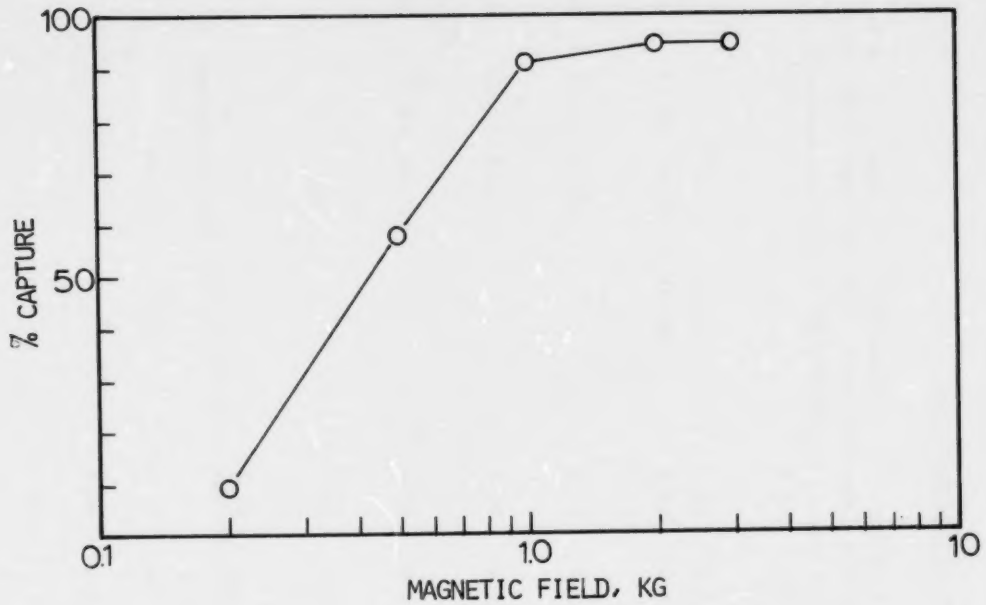



Figure 4. Magnetite capture (Davis Tube) as a function of magnetic field. Feed = 150 gms. with a dispersant (Alconox).

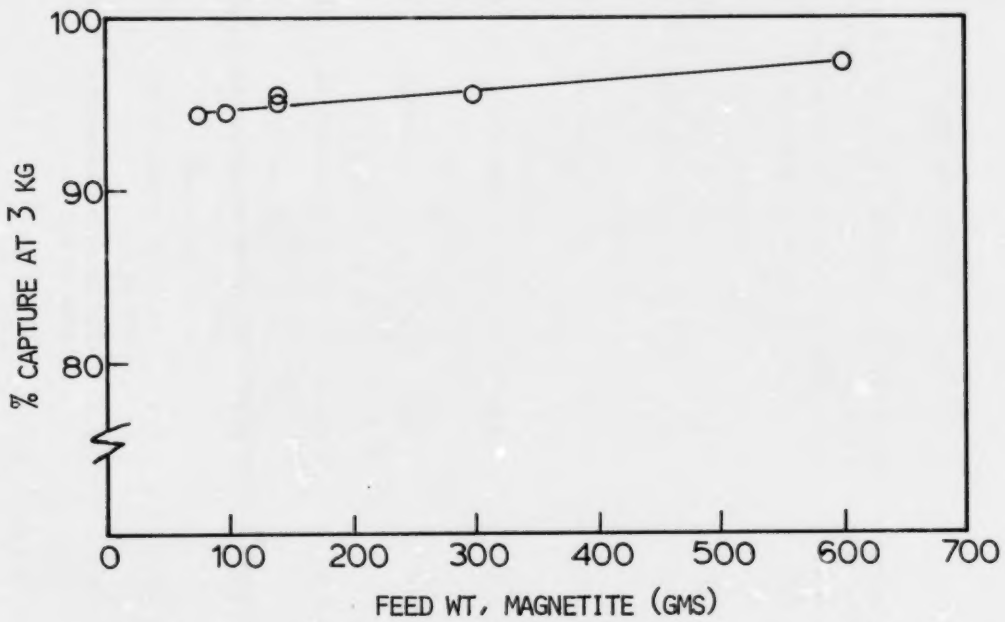



Figure 5. Matrix loading (magnetite) as a function of feed weight Field = 3.0 kG.

## APPROACH

Magnetite recovery in a heavy-medium coal-washing plant is generally performed by drain and rinse screens and drum magnetic separators. As finer sizes of coal are washed, new techniques will be used. In the accompanying flow sheet for the Homer City coal-washing plant of the Penelec Co. shown as Fig. 6, there is a heavy-medium cyclone which receives the underflow of a 2 mm x 0 classifying cyclone which makes a split at 100 mesh. Thus, the cyclone input is sized at 2mm x 100 mesh. The specific gravity is maintained at 1.30 in the heavy-medium cyclone. The cyclone overflow is a clean coal product containing part of the magnetite medium, and the underflow is refuse and middlings also containing part of the medium. Both of these streams are pumped to magnetic separators for magnetite recovery.

Normally, we might have approached the problem of magnetite recovery by securing samples of the overflow and underflow products from the cyclone and processing these by HGMS, but these were not available. We considered the problem of handling the wide range of particle sizes (2 mm by 0) to be a major problem in operating the separator because a HGMS is a matrix-type separator. Therefore, rather than try to split two output streams at some arbitrary particle size, the input coal size range was chosen with the thought that we might make a particle size split at, say 20 mesh and try to handle these fractions separately. A quick test was tried using the coal as received and an attempt was made to design a matrix to handle this wide size range. About 100 experimental trials were conducted with various combinations of matrices and magnetic field configurations. Much information about operating parameters was obtained. Screen spacing, flow rates and distribution of magnetics in the matrix were all varied.

A matrix design was developed which could accept a wide particle size range, retain essentially all the magnetite entering it and pass the coal with low loss values. Clogging the matrix was a problem with earlier designs but the final form escapes this difficulty. After this matrix was designed, most of the experimental runs used the coal as received mixed with magnetite in the proportions indicated in Fig. 7 for the case of specific gravity = 1.30. Some runs were made on the magnetite and coal by themselves

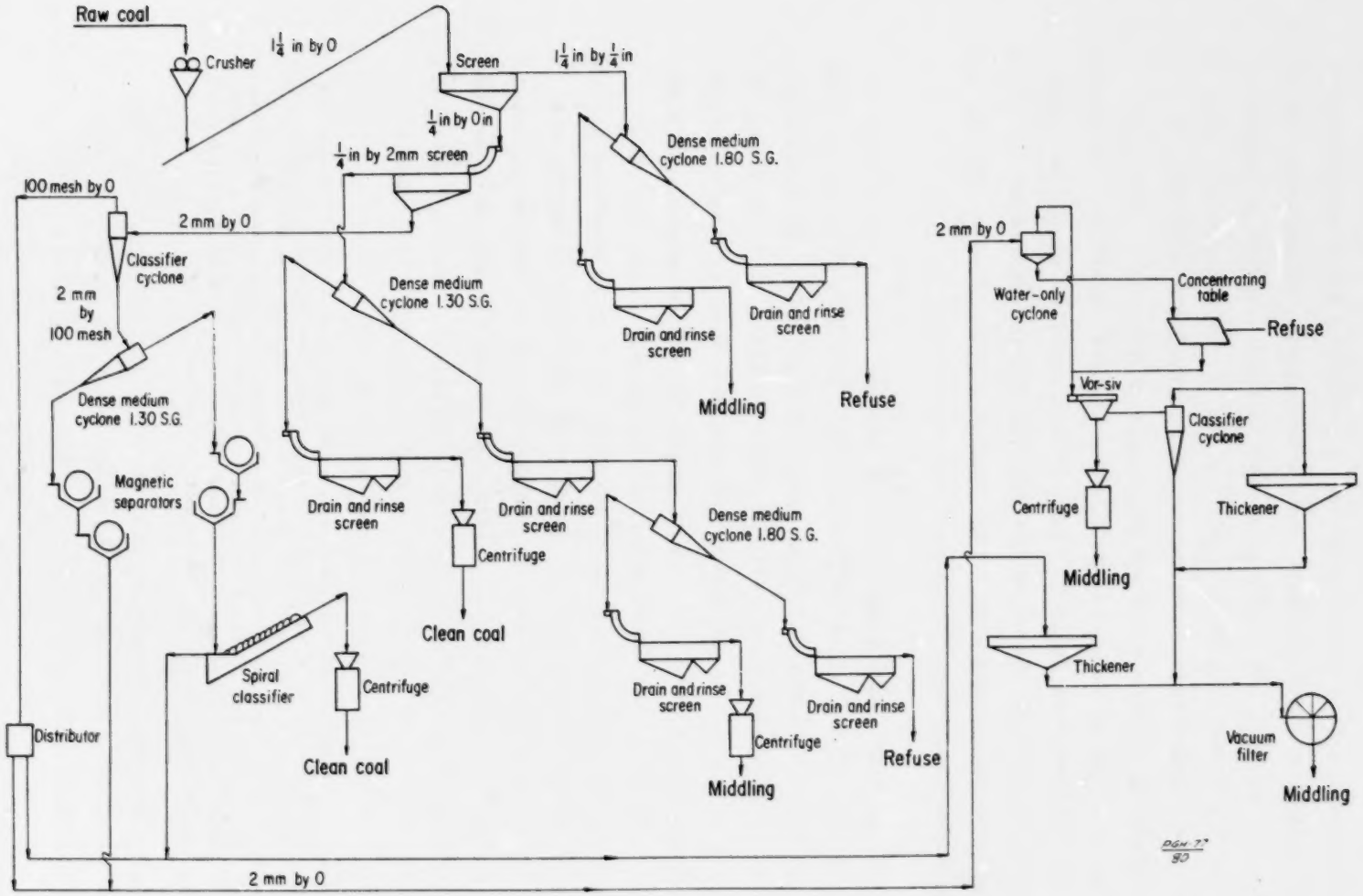
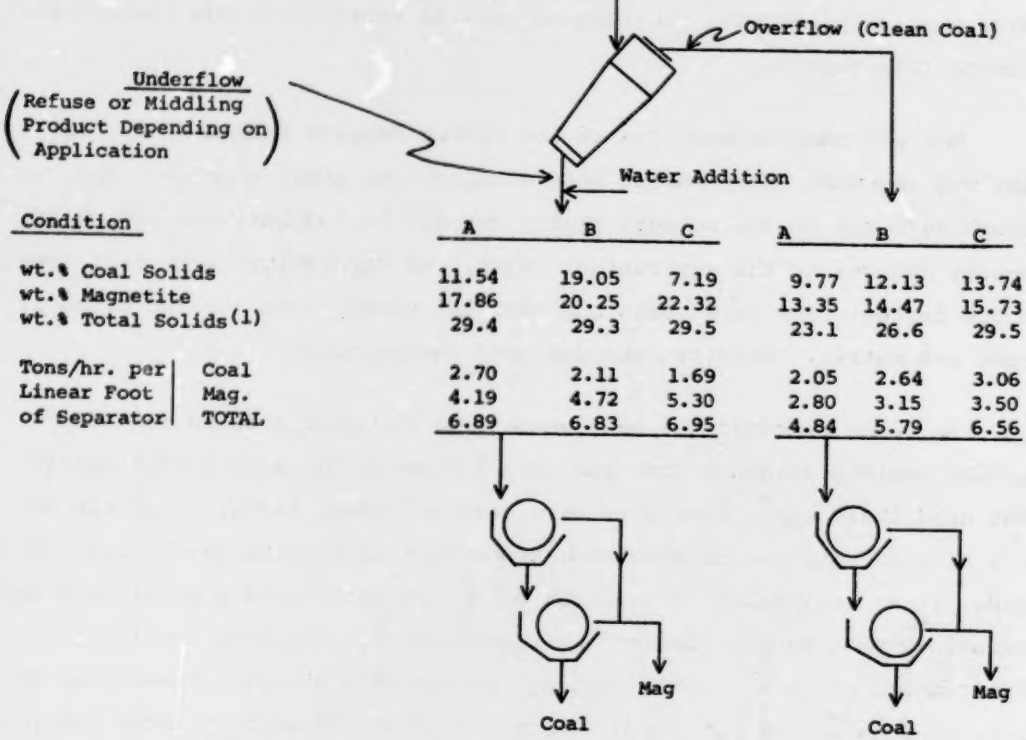



Figure 6. Schematic of the Homer City Coal Cleaning Plant (simplified circuit). Feed samples are similar to feed (2 mm x 100 mesh) to cyclone on left.

| Condition | A | B | C |
|---|---|---|---|
| Average Sp. Gr. of Separation | 1.275 | 1.300 | 1.325 |
| % Coal Solids (by wt.) | 13.7 | 13.4 | 13.14 |
| % Magnetite Solids (by wt.) | 20.1 | 22.2 | 24.24 |
| % Total Solids (by wt.) | 33.8 | 35.6 | 37.4 |
| Specific Gravity of Feed | 1.249 | 1.274 | 1.299 |




| Condition | | A | B | C | A | B | C |
|---|---|---|---|---|---|---|---|
| wt.% Coal Solids | | 11.54 | 19.05 | 7.19 | 9.77 | 12.13 | 13.74 |
| wt.% Magnetite | | 17.86 | 20.25 | 22.32 | 13.35 | 14.47 | 15.73 |
| wt.% Total Solids(1) | | 29.4 | 29.3 | 29.5 | 23.1 | 26.6 | 29.5 |
| Tons/hr. per Linear Foot of Separator | Coal | 2.70 | 2.11 | 1.69 | 2.05 | 2.64 | 3.06 |
| | Mag. | 4.19 | 4.72 | 5.30 | 2.80 | 3.15 | 3.50 |
| | TOTAL | 6.89 | 6.83 | 6.95 | 4.84 | 5.79 | 6.56 |

NOTE. (1) wt.% total solids leaving H.M. cyclone underflow is 50%. Values shown are after dilution by the water addition indicated to provide a more acceptable slurry mix to the magnetic separators.

Figure 7. Homer City Station Coal Preparation Plant fine coal (2 mm x 100 mesh) heavy medium cyclone circuit flow ratios to heavy medium cyclones and to magnetic separators for magnetite recovery.

and the results are indicated under the section on feed.

In order not to ignore the fact that the separator would operate in practice on the output streams of a 1.30 specific gravity, heavy-medium cyclone, 10% of our 200 pounds of coal was split in an organic liquid at 1.30 specific gravity by Eastern Associated Coal Corp. The products of this split were run through the separator with magnetite after the parametric studies on the coal-magnetite samples had been completed. The results are compared with the runs on coal as received in the results section of this report.

Not all samples were run at the slurry density indicated in Fig. 7. That was somewhat inconvenient when working with small samples. But enough were run at the correct slurry density to indicate the effect of density changes on the separation. Also, the separations were performed at the fastest flow rates possible with the slurry tank located directly above the matrix. Gravity feed was used exclusively.

No water preceded the samples through the matrix as is customary in HGMS testing although some was used following the slurry to maintain what head there was. Some runs were done at slower flows to see the effect of flow rate and to determine the effect of filling the matrix beforehand. It is inevitable in research on an application of a relatively new technology that machine design and process design get done together to some extent. This was not a testing program of a standard commercial device, so much of the work here was done to give information about the process and machine requirements.

All experimental work on this project consisted of single passes through the separator. Multiple passes, and their contribution to the

process, were left to a second phase of this work. Single pass means one machine in practice, and if coal and magnetite can be separated by one machine, capital costs are held to a minimum. We decided to follow this plan as far as we could and, as it turned out, we never felt the need nor had time to investigate multiple passes. We will note in a section on recommendations for future work, though, that this possibility should not be ignored.

## APPARATUS AND EXPERIMENTAL METHOD

A dipole magnet consisting of two water-cooled coils surrounded with iron — forming pole faces 7" x 24" in face area and 2" apart — was used for most of the experiments. This magnet is capable of producing a magnetic field of 21,300 gauss, partly because of the massive iron structure. The current required to produce this field is 650 amperes at 70.5 volts. The field values were measured with a transverse probe used on a Bell gaussmeter. Some earlier runs were done on a 10,000 gauss solenoid magnet driven by the same power supply. The current for the dipole magnet was measured by a millivoltmeter placed across a shunt.

The field values used in this experimental work were in the range of 0-6000 gauss. This range was determined by experimentation with magnetite trapping as a function of field. The residual field in the iron structure was of the order of 100 gauss, depending on the magnetization history of the iron. It seemed to have no effect on the cleaning of the magnetite from the matrix. Therefore, we took no precautions to reduce this to zero although this is easy to do.

The separator itself consisted of an aluminum tube of 4.8 sq. in. cross-section filled with stainless steel expanded-metal screens. This material was a necessary substitute for steel wool used so often in HGMS experiments and in commercial practice because of the wide particle size range of the feed samples. It also is more difficult to plug this open structure with magnetite. The outlet of this tube was open for maximum flow rates and later restricted by a valve for controlled flow and attachment of further flow restrictors.

The samples were slurried in a head tank with adequate stirring provided by two propellers on a laboratory stirrer. Baffles prevented vortices and a plug was used to prevent premature solids entry into the separator. Details of the apparatus are shown in Fig. 8.

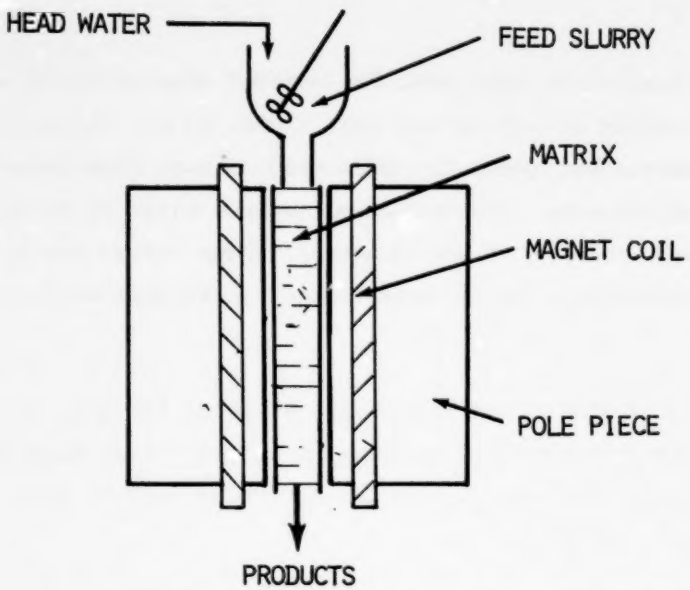



Figure 8. Schematic of experimental apparatus. The magnet gap is 2" by 7" between the pole pieces. Fields of 21 kG can be obtained.

A dispersant (Alconox) was used in some of the experimental runs to reduce magnetic agglomeration but later runs were made without it for comparison.

A Denver 8" pressure filter was used to dewater the products. Samples were air-dried and weighed before further analysis. A HIAC Particle Analyzer was used to analyze samples taken directly from the feed and product slurries. The filter changes the particle size distribution radically, therefore samples were taken from the slurries.

The method of running tests consisted of sampling both magnetite and coal in a careful way and mixing them in the slurry for several minutes. In the mode of unrestricted flow the slurry was allowed to flow by gravity through the separator and the products collected at the outlet. The time was recorded for the total products recovery and in some cases for differential volumes. Magnetics were washed out with water when the field was off. No backwashing was found to be necessary although the distribution of material in the matrix usually would make backwashing advantageous.

Flow restrictors were used for several sets of tests so that values for the throughput of solids and superficial slurry velocities would be accurately known, but generally this reduction in flow rate degraded the separator performance. The throughput values range up to 4 tph/$ft^2$ and the flow rates up to about 300 gpm/$ft^2$. These values are the lowest of a range of throughputs to be investigated in further work.

Magnetic field values were kept as low as the data on magnetite recovery vs. field would allow because low field values mean cheaper magnets. However, we find that work in the future might well be done at slightly higher fields.

Other analyses obtained were iron, sulfur, and ash. A few float-sink determinations on a number of the products to detect a loss of coal (defined as 1.30 float product) were done quickly at the end of the project. They indicated very low losses (1%) of float product in a number of tests but suffered from poor material balances.

Although the length of the matrix was dictated somewhat by the magnet configuration and we made no further attempts at improving matrix design, loading was investigated because it would be important to know if there were serious limitations in this regard.

## ANALYSIS METHODS

### Magnetics

A Magnos MXM-3 integrating fluxmeter was obtained and a coil designed for it. Capsules filled with samples were placed in the coil, the magnetometer was zeroed, and the capsule removed thereby changing the total flux through the coil. This change is integrated by the fluxmeter as a voltage-time product. Calibration samples were made up from the coal and magnetite, and the calibration curve is shown as Fig. 9 to indicate that the curve passes through zero and that there is very little scatter in the points. The method is sensitive to about 0.1% magnetite.

Magnetics in some of the run products were measured by Davis Tube at the Bureau of Mines Coal Preparation and Analysis Laboratory. These values are given in parentheses in the data tables.

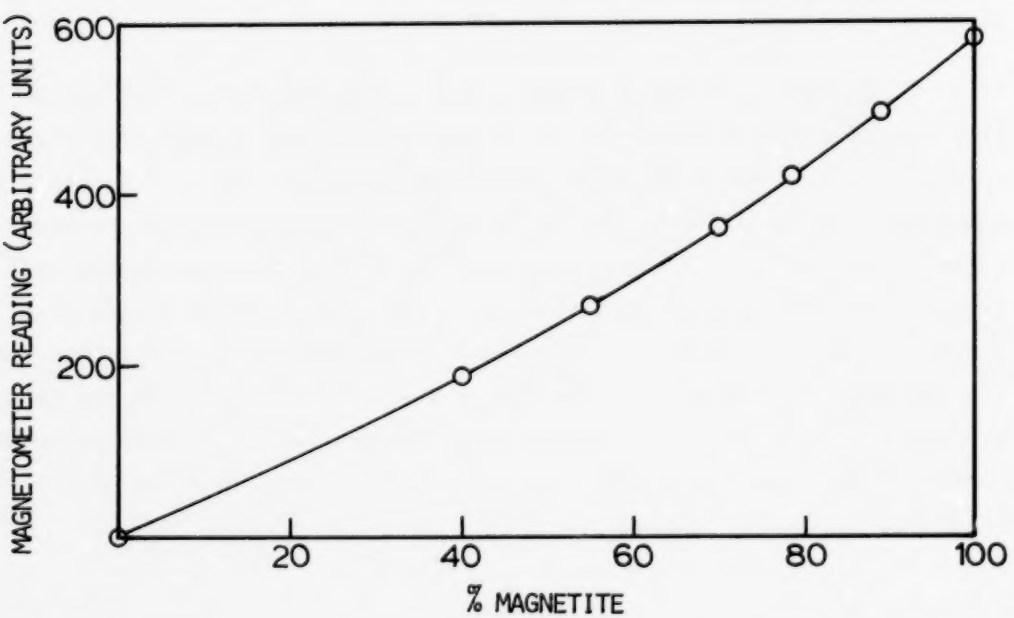



Figure 9. Calibration curve for the integrating magnetometer. Standards were made of the feed coal and magnetite.

Iron

All iron analyses were done by Lerch Bros. Inc. by wet chemistry or by flame spectrometry (atomic absorption).

Ash

Ashing was done by the standard ASTM method at M.I.T. Materials balances are shown in the Appendices for ash and iron analyses. Also in an Appendix is a correlation between magnetics, ash and iron results.

Particle Size Analysis

We obtained a HIAC Particle Analyzer for this project to investigate the effectiveness of HGMS on recovery of fine magnetite. The HIAC PC-320 works on the light blockage principle. Particles are carried through a sensor by a fluid under pressure with the flow rate of the transport fluid well controlled by means of a pressure valve, and thus the possibility of coincidence, i.e., of two particles passing through the sensor simultaneously, can be minimized. The particle is described in terms of its equivalent sphere diameter which is the diameter of a sphere with a cross-sectional area equal to the projectional area of the particle.

Originally we sampled the magnetite solutions using the "volume sample" option of the HIAC PC-320 which would count the number of particles in each size channel in a given amount of solution. We used a method of sampling as much of the total sample as possible to minimize the problem of settling. Stock solutions were made up of dry material shaken well in 250 ml of water. Then approximately 20 ml of the stock solution was diluted by an equal amount of distilled water and stirred well. The HIAC was run such that it would count the number of particles from the first drop of new solution until stopped when the meniscus of the solution hit a mark on the sampling tube. Thus it would run through 35 ml of solution leaving 5 ml in the beaker.

In some suspensions Alconox was used to see if its presence could inhibit agglomeration. Methanol was also tried to "wet" the material. Neither appeared to be significant. Nor was glycerin which was used to try to slow the settling rate. The figures were all corrected by subtracting baseline values obtained by sets of distilled $H_2O$ runs done at the beginning and end of each determination.

## RESULTS

### Magnetite Capture and Coal Recovery as a Function of Magnetic Field

In Table 9, data is presented for a series of runs made at increasing magnetic fields up to 6000 gauss. The samples were coal and magnetite in the proportions found in the cyclone feed and a dispersant was used to reduce magnetic agglomeration. The solids density is less than specified for the cyclone feed but we will present data on the effect of solids density further on. The throughput is the weight of total solids in the feed divided by the time taken to pass through a cross-section of the separator.

Runs 114 through 119 were preliminary runs made on the newly constructed double screen matrix and show some very good results particularly run 116 at 2 kG. Runs 120-126 are a more carefully controlled set of runs done with increasing values of field.

The values for magnetics contained in both separator products were determined both by our magnetometer and by Davis Tube. At the higher fields the loss of magnetics to the non-mags fraction is of the order of tenths of a percent. In Fig. 10, we show this data to give an idea of the correspondence of these methods, and the effect of magnetic field. Our magnetometer gives higher readings because we define the as received magnetite to be 100% magnetics.

The values of magnetics loss to the non-mags are corroborated by the values of ash which are asymptotic to the ash value in the coal (13.2%) as the field increases. Coal loss is shown in Table 9 by percent ash in the mags, percent magnetics or percent iron (coal = 2.33% iron).

In Fig. 11 is shown the percentage of the feed captured vs. magnetic field in order to determine the field necessary for successful separation. The curve is essentially flat above 2 kG. The feed is 62.4% Reiss-Viking magnetite and this curve seems to be asymptotic to 64% capture. As was shown earlier, only a few tenths of a percent of the coal should be captured and about 4% of the magnetite should escape capture so there is an

TABLE 9

The Effect of Magnetic Field

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | SAMPLE | % WEIGHT non-mags | % WEIGHT mags | % MAGNETICS non-mags (Davis Tube)† | % MAGNETICS mags (Davis Tube)† | % IRON non-mags | % IRON mags | % ASH non-mags | % ASH mags |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 114 | 0.5 | 2.3 | 150.00 gm R-V magnetite<br>90.54 gm coal<br>1305 ml $H_2O$<br>20 ml dispersant *<br>15.6% solids by weight | 56.6 | 43.4 | 37.2<br>(32.1) | 100.3<br>(91.9) | 24.25 | 61.67 | | |
| 115 | 1.0 | 3.4 | SAME | 40.0 | 60.0 | 13<br>( 6.9) | 95.8<br>(89.7) | 9.42 | 60.82 | | |
| 116 | 2.0 | 3.9 | SAME | 36.8 | 63.2 | 0.2<br>( 0.4) | 100.0<br>(88.5) | 3.70 | 60.82 | 22.4 | 96.3 |
| 118 | 5.0 | 3.3 | SAME | 31.3 | 68.7 | 0 | 88.2 | 3.02 | 56.15 | 19.3 | 92.7 |
| 119 | 6.0 | 3.9 | SAME | 31.8 | 68.2 | 0.1 | 91.1 | 2.82 | 56.11 | | 93.0 |
| 120 | 0.5 | 1.2 | SAME | 72.4 | 27.6 | 46.4<br>(42.9) | 103.1 | 29.79 | 64.20 | 58.0 | 100.0 |
| 121 | 1.0 | 3.0 | SAME | 44.7 | 55.3 | 18.2<br>(14.3) | 98.7<br>(91.8) | 17.23 | 69.43 | 33.5 | 97.9 |
| 122 | 2.0 | 3.8 | SAME | 36.3 | 63.7 | 1.1<br>( 0.2) | 95.8<br>(88.2) | 3.58 | 75.63 | 20.7 | 96.2 |
| 123 | 3.0 | 4.4 | SAME | 36.0 | 64.0 | 0.8<br>( 0.1) | 96.5<br>(88.6) | 3.70 | 60.27 | 22.3 | 97.5 |
| 124 | 4.0 | 4.1 | SAME | 36.4 | 63.6 | 0.5<br>( 0.3) | 95.7<br>(88.4) | 3.25 | 59.47 | 20.1 | 98.0 |
| 125 | 5.0 | 4.2 | SAME | 36.3 | 63.7 | 0.3<br>( 0.2) | 101.0<br>(88.8) | 3.25 | 60.55 | 15.6 | 97.5 |
| 126 | 6.0 | 3.9 | SAME | 35.2 | 64.8 | 0.4<br>( 0.2) | 97.4<br>(89.0) | 3.04 | 60.60 | 15.0 | 97.8 |

* Dispersant: 10 gm Alconox/liter

† Davis Tube values for magnetite are 90-91%, for coal 0

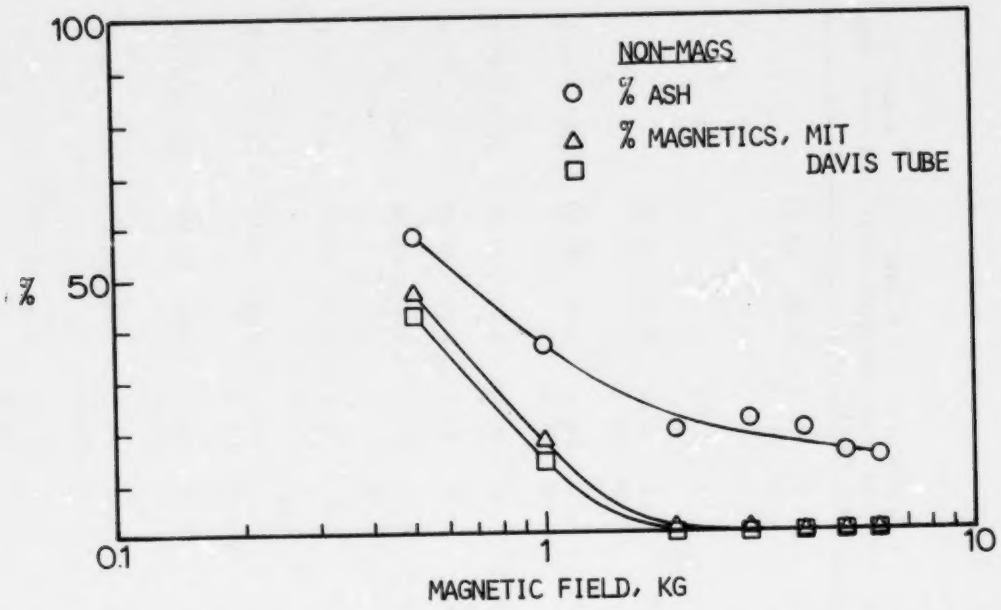



Figure 10. Ash and magnetics measurements for the non-mags as a function of magnetic field.

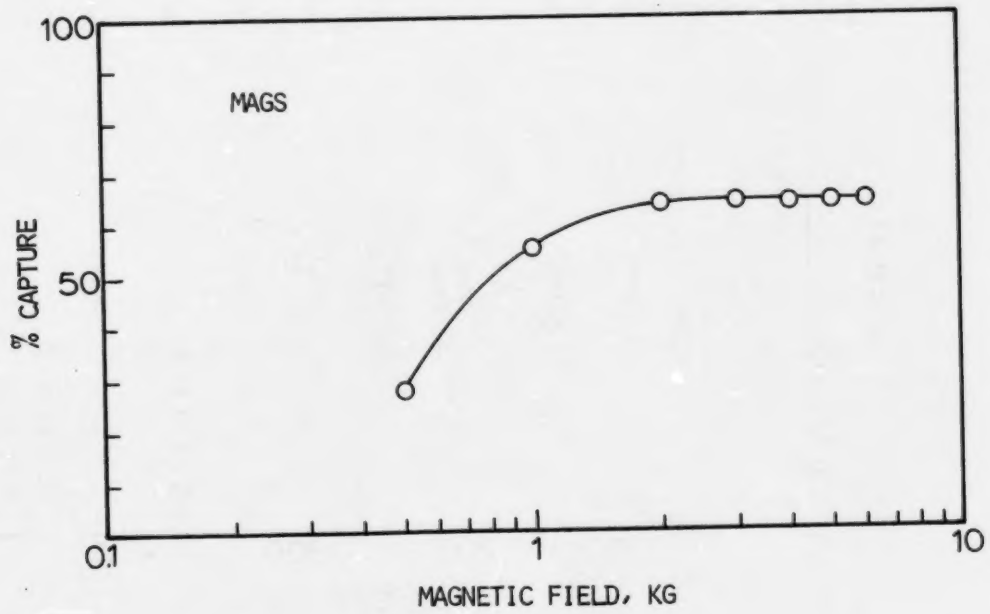



Figure 11. Magnetics capture (% of feed) as a function of field. Feed = 150 gms magnetite, 90.5 gms coal at 15.6% solids. Average throughput = 3.5 tph/ft$^2$. (Table 9)

uncertainty as to the path followed by the impurities. This curve indicates that part of them reports to the magnetics.

Matrix Loading When Samples Consist of Both Coal and Magnetite

In Table 10 and Fig. 12 the percent capture at 3 kG is compared to the weight of magnetite in the feed. In each case, the feed contained 37.6% coal by weight as in almost all other runs. In fact, this data was selected from several series of runs made for other purposes. The conditions are somewhat different for different series of runs, therefore they are plotted separately. Runs 123, 127-130 have the highest throughput values because a valve was added to accommodate flow restrictors just after these runs were made and,even though no flow restrictors were used in any runs, the later ones had lower throughputs on the average with the valve in place.

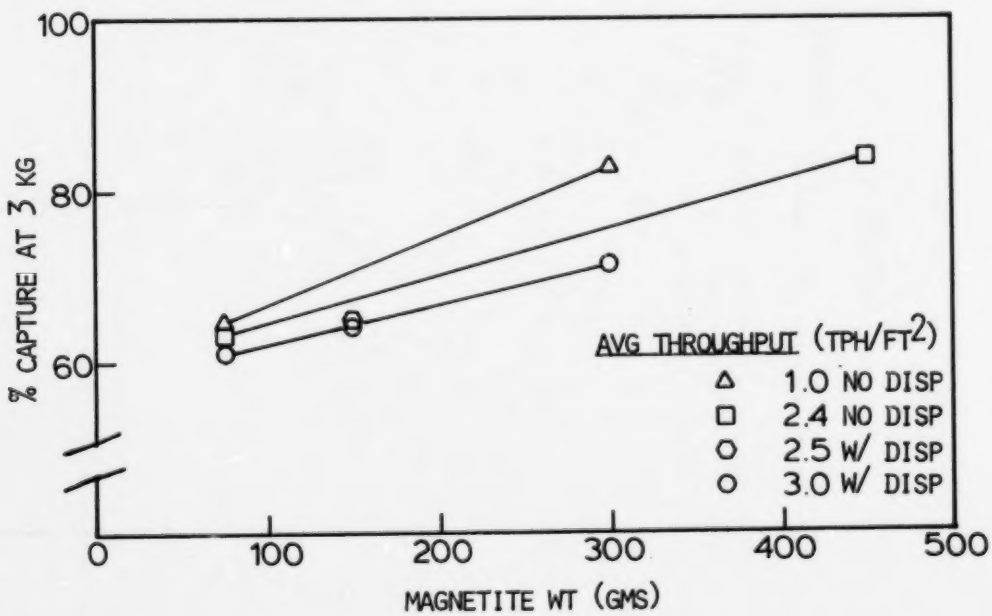



Figure 12. Magnetics capture at 3 kG as a function of feed weight expressed as weight of magnetite.

TABLE 10

Effect of Matrix Loading

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | R-V*MAGNETITE FEED WT. (gm) | % SOLIDS | DISPER-SANT † | % WEIGHT non-mags | % WEIGHT mags | % MAGNETICS (Davis Tube) non-mags | % MAGNETICS (Davis Tube) mags | % IRON non-mags | % IRON mags | % ASH non-mags | % ASH mags |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 148 | 3.0 | 1.2 | 75 | 8.4 | | 35.5 | 64.5 | 0.6 (0.1) | 96.8 (87.5) | 3.61 | 60.60 | | |
| 129 | 3.0 | 1.9 | 75 | 8.4 | √ | 39.5 | 60.5 | 1.3 | 102.2 | 3.33 | 63.60 | | |
| 163 | 3.0 | 1.9 | 75 | 8.4 | | 37.0 | 63.0 | 1.2 | 96.7 | 3.90 | 61.81 | 18.7 | 98.9 |
| 127 | 3.0 | 2.9 | 75 | 8.4 | √ | 38.5 | 61.5 | 0.6 | 99.7 | 3.81 | 62.08 | | |
| 158 | 3.0 | 2.5 | 150 | 15.6 | √ | 35.3 | 64.7 | 2.3 | 94.8 | 3.42 | 58.91 | 20.9 | 95.8 |
| 123 | 3.0 | 4.4 | 150 | 15.6 | √ | 36.0 | 64.0 | 0.8 (0.1) | 96.5 (88.6) | 3.70 | 60.27 | 22.3 | 97.5 |
| 149 | 3.0 | 0.8 | 300 | 27.0 | | 17.4 | 82.6 | 0.6 | 77.0 | 3.25 | 46.27 | | |
| 147 | 3.0 | 0.9 | 300 | 27.0 | | 17.4 | 82.6 | 3.0 | 74.6 | 8.27 | 47.96 | | |
| 128 | 3.0 | 2.7 | 300 | 27.0 | √ | 29.1 | 70.9 | 1.0 | 87.9 | 3.61 | 55.34 | | |
| 130 | 3.0 | 3.5 | 300 | 27.0 | √ | 27.4 | 72.6 | 1.1 | 87.3 | 2.97 | 54.06 | | |
| 165 | 3.0 | 0.5 | 450 | 35.6 | | 16.5 | 83.5 | 1.2 | 74.4 | 3.50 | 45.53 | | |

† Dispersant: 20 ml of 10 gm Alconox/liter

* Feed: 62.4% R-V magnetite, 37.6% coal

In all cases the total capture increases with loading. Coal or impurities or both report to the magnetics as the amount of magnetite trapped on the matrix increases. The runs at the highest throughputs exhibit the lowest entrainment and it remains to be seen how little coal loss can be achieved as throughputs are increased in future work.

All runs at the 75 gm loading have less than 5% of the non-mags reporting to the magnetics and the high throughput run 123 (4.4 tph/$ft^2$) has a non-mag loss at 150 gms loading of less than 5%. We consider this throughput value to be at the bottom of the range of values possible with HGMS operating in the mode of unrestricted flow.

Magnetics recovery seems unaffected by loading as shown by the percent magnetics in the non-mags. Even at 450 gms only 0.33% of the 450 gms of magnetite ends up in the non-mags. This seems to agree with the loading data obtained for magnetite alone (see the section on feed materials, Fig. 5).

Magnetite Recovery at Cyclone Input Slurry Density

The effect of high slurry density (35.6 solids) and high loading (300 gms magnetite) can be seen in Table 11. Some magnetite is lost to the non-mags as evidenced by the magnetics and iron values although it is evident from Fig. 13 that magnetite recovery is increasing sharply with magnetic field and presumably will reach an acceptable value at the 6 kG field used in several previous runs.

TABLE 11

Effect of High Slurry Density

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | SAMPLE | % WEIGHT non-mags | % WEIGHT mags | % MAGNETICS* non-mags | % MAGNETICS* mags | % IRON non-mags | % IRON mags |
|---|---|---|---|---|---|---|---|---|---|
| 166 | 1.0 | 0.8 | 300.00 gm R-V magnetite<br>181.08 gm coal<br>870 ml $H_2O$<br>35.6% solids by weight | 67.1 | 32.9 | 64.3 | 82.5 | 35.32 | 47.18 |
| 168 | 1.0 | 1.4 | SAME | 76.3 | 23.7 | 55.0 | 86.3 | 34.95 | 54.30 |
| 167 | 2.0 | 1.0 | SAME | 52.9 | 47.1 | 45 | 83 | 27.98 | 47.61 |
| 169 | 2.0 | 1.4 | SAME | 58.0 | 42.0 | 55 | 75 | 30.74 | 49.30 |
| 170 | 4.0 | 1.1 | SAME | 36.3 | 63.7 | 32.0 | 85.5 | 18.04 | 51.98 |

* By magnetometer

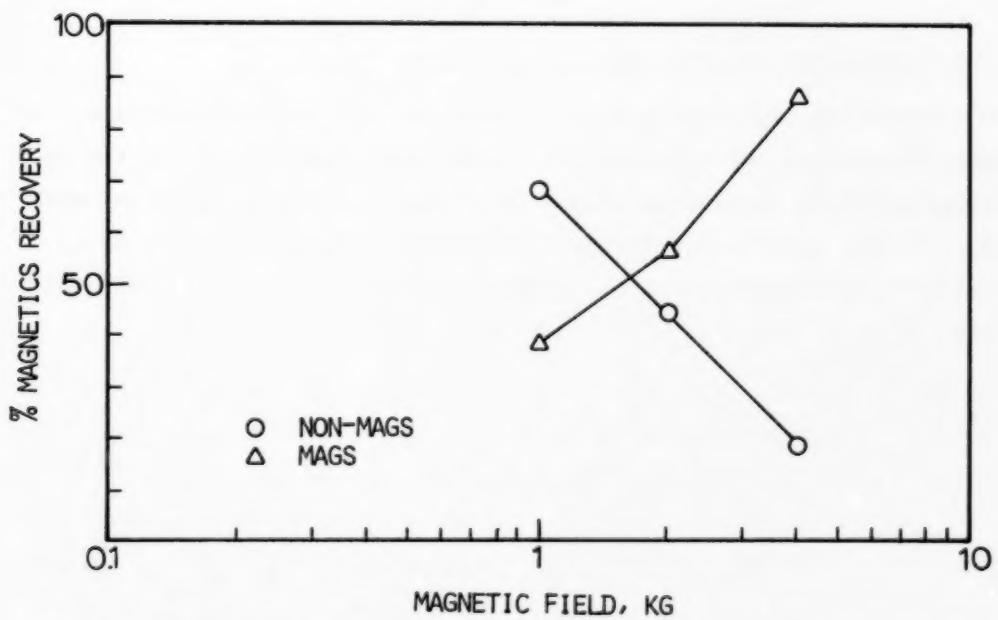



Figure 13. Magnetics recovery from samples twice the usual feed weight and at 35.6% solids (= density of cyclone feed). Recovery is defined as ratio of magnetics weight in products to that in the feed. (Table 11)

Cyclone Products Tests

The preceding tests were all conducted on cyclone feed. In order to test the effectiveness of HGMS on the products of the heavy-medium cyclone where the magnetic separators would most likely be placed, a coal sample was split at 1.30 specific gravity in an organic liquid. The products of the split were 48.4 percent float by weight and 51.6% sink. These were tested by mixing with magnetite (in the proportions shown on the Homer City flow sheet) and subjected to HGMS under conditions similar to the previous testing.

1. Sink Product (1.30)

This simulates the cyclone underflow and feed samples were made up as stated above. The solids density was 29.3% as specified in the cyclone flow sheet provided by Pennelec (shown as Fig. 7). Runs were made at 2 kG and 4 kG with no flow restrictor and also restricted to 4 gpm. All runs were repeated. The results are shown as Table 12. The total material capture is higher at the slower flow rates and, at the higher field values, the percent magnetics measured in the non-mags reaches a low value of 0.2%.

2. Float Product (1.30)

The feed for these tests approximates the cyclone overflow in the proportions of magnetite and coal. The solids density was 23.3%, about 3.3% less than called for on the Pennelec flow sheet. Results are shown in Table 13.

At a restricted flow rate we retain essentially all the magnetite (see percent magnetics in non-mags, percent iron, or ash) but apparently sustain a coal loss as seen in the figures for ash and iron in the mags (for magnetite 63.3% iron, 102.4% ash). In the case of unrestricted flow the coal loss

TABLE 12

Separation Tests on Sink Product (1.30)

| RUN | MAGNETIC FIELD (kG) | VELOCITY (cm/sec) | SAMPLE | % WEIGHT | | % MAGNETICS* | | % IRON | | % ASH | | FLOW RESTRICTION (gpm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | non-mags | mags | non-mags | mags | non-mags | mags | non-mags | mags | |
| 183 | 2.0 | 87.4 | 150.00 gm R-V magnetite<br>67.04 gm coal (sink 1.30)<br>523.7 ml $H_2O$<br>29.3% solids by weight | 32.7 | 67.3 | 19.4 | 88 | 13.99 | 59.63 | 36.9 | 98.8 | - |
| 188 | 2.0 | 87.4 | SAME | 29.6 | 70.4 | 4.8 | 96.1 | 8.18 | 60.11 | 34.1 | 98.7 | - |
| 185 | 2.0 | 47.1 | SAME | 22.7 | 77.3 | 0.8 | 89.9 | 5.53 | 53.62 | | | 4 |
| 189 | 2.0 | 52.1 | SAME | 21.3 | 78.7 | 0.4 | 89.1 | 5.01 | 54.71 | | | 4 |
| 184 | 4.0 | 112.4 | SAME | 31.7 | 68.3 | 6.3 | 96.4 | 8.58 | 61.76 | 34.6 | 99.9 | - |
| 186 | 4.0 | 87.4 | SAME | 28.9 | 71.1 | 0.6 | 94.7 | 5.65 | 60.92 | 30.7 | 99.5 | - |
| 187 | 4.0 | 46.3 | SAME | 20.2 | 79.8 | 0.6 | 88.2 | 5.05 | 55.54 | | | 4 |
| 190 | 4.0 | 49.8 | SAME | 21.6 | 78.4 | 0.2 | 87.3 | 4.73 | 54.54 | | | 4 |

* By magnetometer

TABLE 13

Separation Tests on Float Product (1.30)

| RUN | MAGNETIC FIELD (kG) | VELOCITY (cm/sec) | SAMPLE | % WEIGHT | | % MAGNETICS* | | % IRON | | % ASH | | FLOW RESTRICTION (gpm) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | non-mags | mags | non-mags | mags | non-mags | mags | non-mags | mags | |
| 191 | 2.0 | 88.4 | 150.00 gm R-V magnetite<br>125.7 gm coal (float 1.30)<br>907.7 ml $H_2O$<br>23.3% solids by weight | 55.7 | 44.3 | 22.8 | 92.2 | 14.95 | 58.35 | 24.2 | 92.5 | - |
| 193 | 2.0 | 49.5 | SAME | 34.7 | 65.3 | 0.2 | 84.5 | 0.56 | 49.97 | 4.3 | 84.1 | 4 |
| 192 | 4.0 | 112.4 | SAME | 44.9 | 55.1 | 13.5 | 91.2 | 6.93 | 57.23 | 10.3 | 92.5 | - |
| 194 | 4.0 | 49.5 | SAME | 35.6 | 64.4 | | | | 51.90 | 3.6 | 85.8 | 4 |

* By magnetometer

drops but the magnetite recovery remains a function of field. A higher field — say 6 kG — would retain more of the magnetite.

Effect of Dispersant on Entrainment at High Solids Density

In Fig. 14, we have plotted the percent mags capture against slurry density for magnetite alone with and without the use of a dispersant. All of these points are at 3 kG and there seems to be little or no effect on the capture. However, there is a significant effect on the coal and magnetite mixtures. The total capture increases from ~63% to ~86% with an increase in percent solids from 8.4 to 35.6. Without a dispersant, the capture increases with an increase in solid density but the effect is reduced considerably with a dispersant.

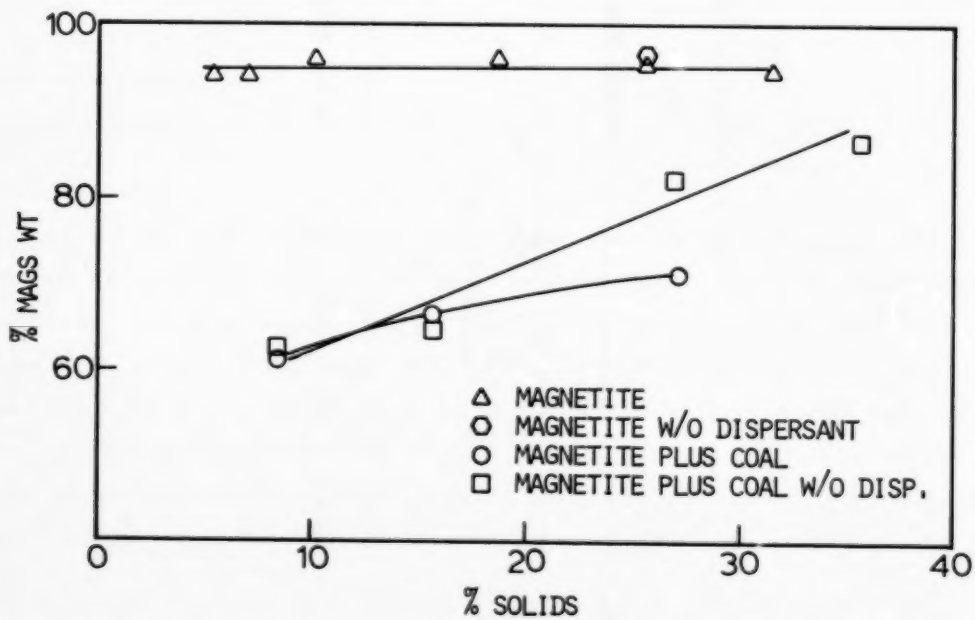



Figure 14. Magnetics capture as a function of feed slurry density for samples of magnetite alone and the same mixed with coal. (H = 3.0 kG). Magnetics capture is % of feed by weight which reports to magnetic fraction.

Restricted Flow Rates

We list in Table 14 several runs made at slower flow rates for the purpose of rate control. Also, the mode of operation of the separator was changed. The matrix was filled with water so that the sample flowed into a matrix already filled. Unfortunately, slower flows have to be used to achieve this condition. The mags fraction increases with decreasing flow rate at each field value and the recovery of magnetic material is affected strongly at the lower field values, but the effect is smaller above 2 kG.

Effect of Dispersant and Other Effects

In Runs 155-162 (Table 15), we repeat the magnetite capture vs. field tests, but use no dispersant. We still have the flow controlling valve in place although no other flow restrictions are used. In these runs we must substitute a higher field to achieve adequate magnetite recovery. This set of runs provides some interesting data since the operating conditions were somewhat better controlled.

In Fig. 15, the percent of feed captured vs. field seems to level off at 65% (62.4% of the feed is R-V magnetite). Figure 16 gives the magnetics recovery in the mags and non-mags.

The percent iron and percent ash are plotted in Fig. 17 for both mags and non-mags. As the field increases, both of these figures increase slowly in the mags as expected but the reduction in the non-mags seems to accelerate until the major part is removed at about 3000 gauss. This may be a magnetic agglomeration effect. Ash and iron contents of the feed coal are shown by arrows on the margin of the graph. As the field increases the ash is reduced to a value higher than that which could be accounted for by the coal so some magnetite or magnetite impurities report to the non-mags.

TABLE 14

Effect of Restricting Flow Rate

| RUN | MAGNETIC FIELD (kG) | VELOCITY (cm/sec) | SAMPLE | % WEIGHT | | % MAGNETICS* | | % IRON | | FLOW RESTRICTION (gal/min) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | non-mags | mags | non-mags | mags | non-mags | mags | |
| 173 | 1.0 | 43.7 | 300.00 gm R-V magnetite<br>181.08 gm coal<br>870 ml $H_2O$<br>35.6% solids by weight | 61.1 | 38.9 | 47.4 | 81.0 | 30.56 | 51.26 | 4 |
| 176 | 1.0 | 29.3 | SAME | 36.0 | 64.0 | 41.9 | 87.7 | 21.96 | 54.06 | 3 |
| 174 | 2.0 | 53.1 | SAME | 25.4 | 74.6 | 1.3 | 81.9 | 3.13 | 50.58 | 4 |
| 177 | 2.0 | 28.1 | SAME | 18.2 | 81.8 | 0.5 | 79.7 | 2.28 | 48.97 | 3 |
| 175 | 4.0 | 43.0 | SAME | 25.0 | 75.0 | 0.4 | 81.1 | 2.65 | 50.58 | 4 |
| 178 | 4.0 | 25.4 | SAME | 21.0 | 79.0 | 0.4 | 76.7 | 2.16 | 48.61 | 3 |

* By magnetometer

TABLE 15

Magnetite Capture Without Dispersant

| RUN | MAGNETIC FIELD (kG) | THROUGHPUT (tph/ft$^2$) | SAMPLE | % WEIGHT non-mags | % WEIGHT mags | % MAGNETICS non-mags (Davis Tube) | % MAGNETICS mags (Davis Tube) | % IRON non-mags | % IRON mags | % ASH non-mags | % ASH mags |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 155 | 0.5 | 1.1 | 150.00 gm R-V magnetite<br>90.54 gm coal<br>1305 ml $H_2O$<br>15.6% solids by weight | 68.9 | 31.1 | 52.8 | 94.9<br>(85.6) | 31.58 | 58.83 | 57.4 | 94.7 |
| 156 | 1.0 | 1.7 | SAME | 56.1 | 43.9 | 40.1 | 94.0 | 23.27 | 59.19 | 49.3 | 95.2 |
| 157 | 2.0 | 2.4 | SAME | 40.8 | 59.2 | 20.6 | 94.3 | 13.14 | 58.67 | 33.2 | 95.0 |
| 158 | 3.0 | 2.5 | SAME | 35.3 | 64.7 | 2.3 | 94.8 | 3.42 | 58.91 | 20.9 | 95.8 |
| 160 | 4.0 | 2.7 | SAME | 35.1 | 64.9 | 0.5 | 96.0 | 3.26 | 59.96 | 19.2 | 96.7 |
| 161 | 5.0 | 2.9 | SAME | 34.9 | 65.1 | 0.5 | 95.3 | 2.41 | 59.07 | 19.6 | 96.2 |
| 162 | 6.0 | 3.1 | SAME | | | | 97.2 | | 60.84 | | 99.3 |

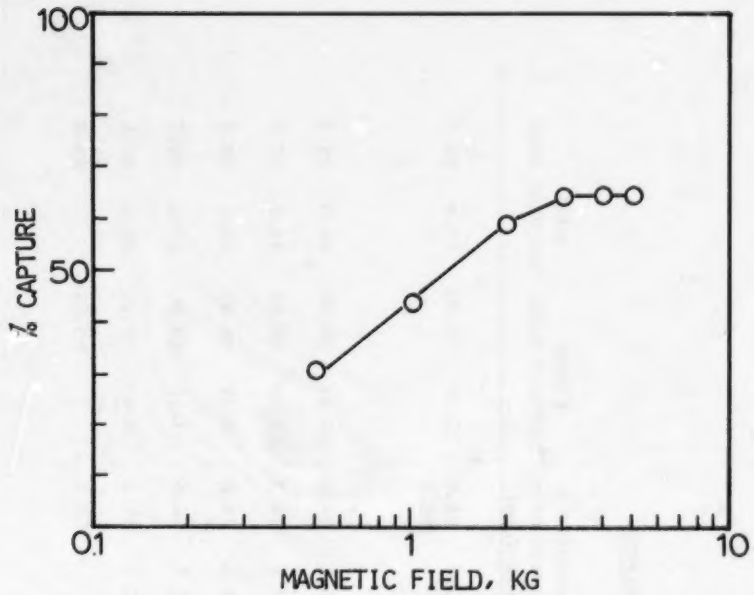



Figure 15. Magnetics capture (% of feed wt.) as a function of magnetic field. No dispersant was used. The feed density was 15.6% solids. Normal feed weight of 240 gms total solids. (Table 15)

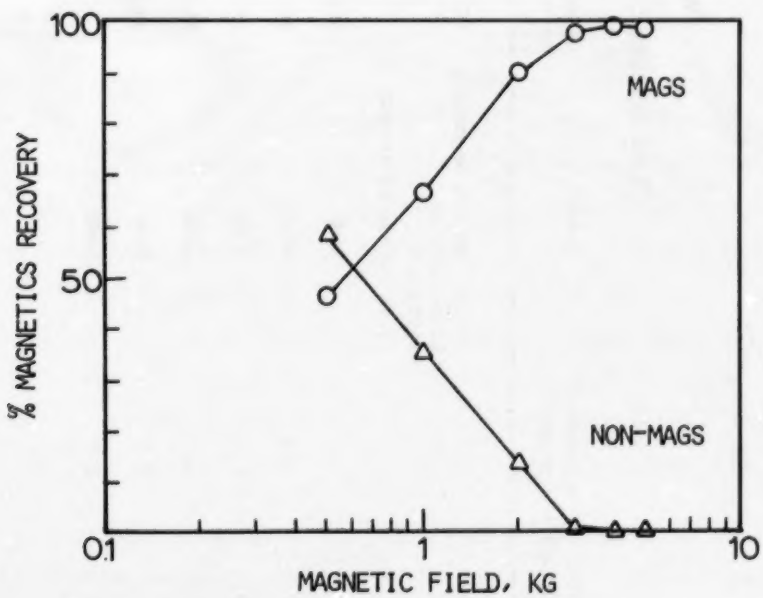



Figure 16. Magnetics recovery (% of magnetics in feed) in both mags and non-mags as a function of magnetic field for the runs without dispersant. (Table 15)

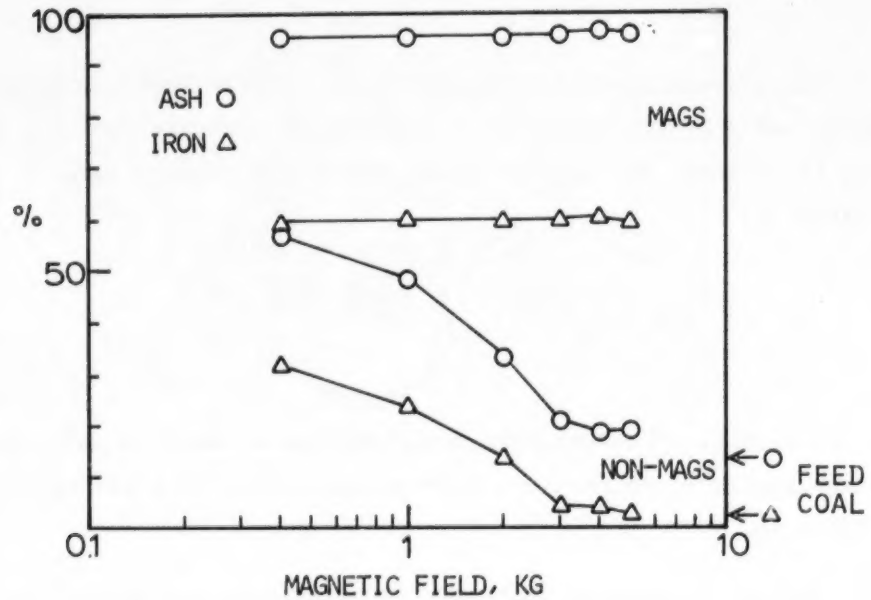
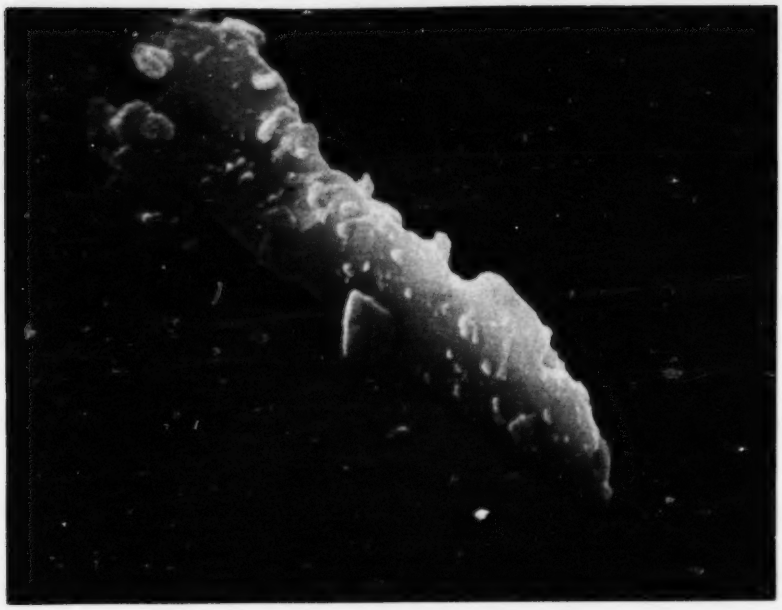



Figure 17. Ash and iron values for non-mags and mags as a function of magnetic field. (Table 15)

Particle Size Analysis

Ten experiments were run in which the feed and products were sampled directly from the slurry for the purpose of particle size analysis. The products of the experimental runs which had been filtered were not suitable for this analysis because filtering alters the particle size distribution. The samples for these runs were all 150 grams of Reiss-Viking magnetite. Eight of these were slurried in tap water which had been used throughout the project. Two samples were slurried in distilled water to reduce the background particle count from the water. A dispersant (Alconox) was used in six runs and left out of the other four. Runs were made to investigate the effect of increasing the magnetic field and in two runs the matrix was not filled with water first.

The data were obtained using the HIAC Particle Analyzer. Numbers of particles per channel (6 channels 1-3, 3-5, 5-8, 8-15, 15-20, 20-60 microns) were recorded, an average particle size diameter per channel chosen and the average weight percentage less than the upper limit of each channel plotted.



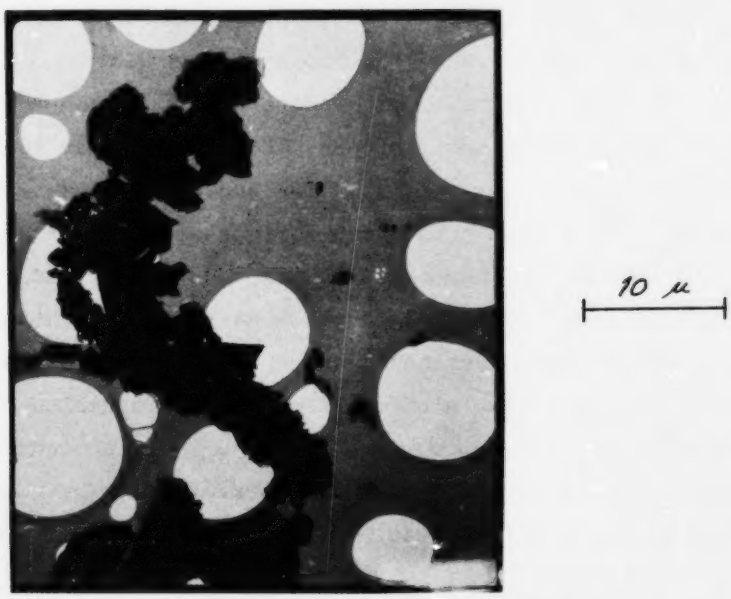




Figure 18. Electron microscope photographs of non-mags particle (top) (Magnification = 11,050) and chained magnetite particles (Magnification = 2,100).

particle assumed for the purpose of particle size measurement is evident.

One of the objects of this analysis was to determine if the separator discriminated in its collection of magnetite on the basis of particle size. The HGMS technique is suited for small particle trapping and we did not expect to lose magnetite fines in any large amount.

Figure 19 shows the results of a distilled water run at 1000 gauss. The feed distribution is considerably above both mags and non-mags. In each size range the weight fraction below a given size is higher in the feed. In other words the feed has more small particles than the products. This is the effect of magnetic agglomeration which shifts the size distribution towards the larger sizes. Note that there is hardly any difference between the mags and non-mags. If the separator failed to attract fine particles but trapped only larger ones, these distributions would be different.

Figure 20 shows results of a run at the same conditions but with a field of 3000 gauss. Here the products have decidedly different distributions. The non-mags have more larger particles and the magnetics contain a larger fraction of smaller ones. For example, at 1000 gauss (Fig. 17) the magnetics have 75% wt. below 20μ and at 3000 gauss (Fig. 18) 89% is below 20μ. This result is certainly caused by an effect other than the loss of fines to the non-mags. An explanation of this effect may be found in the fact that the non-mags are 38.6% of the weight at 1000 gauss and only 3.32% at 3000 gauss and probably consist therefore, at the high field, entirely of impurities with a different size distribution. This may be due to hardness differences which affect the results of grinding. At any rate we do not see at either field any discrimination between mags and non-mags at the smaller particle size.

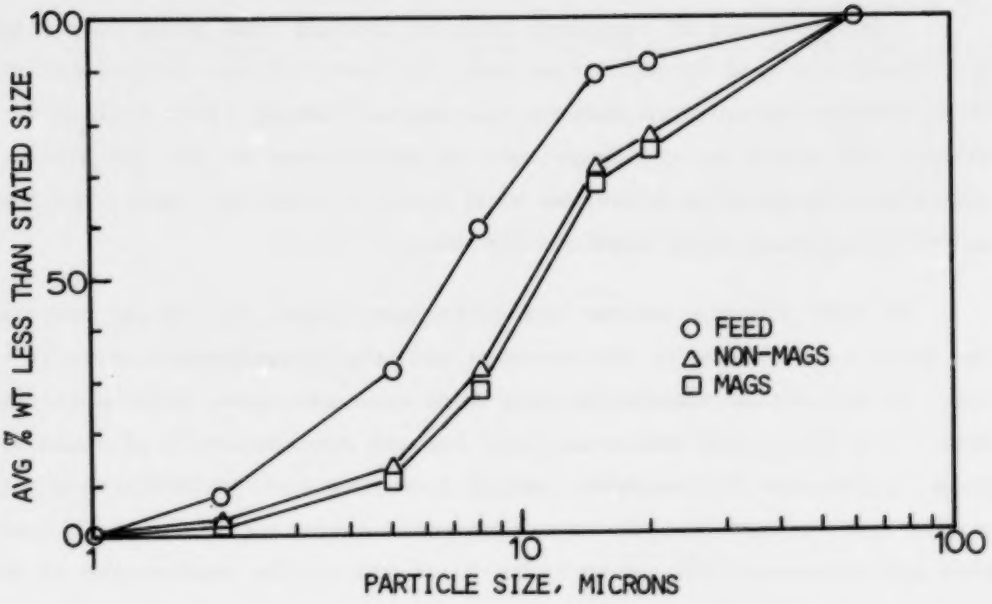



Figure 19. Cumulative particle size distribution of magnetite before and after HGMS. The field was 1.0 kG. No dispersant was used and the matrix was filled with water before running.

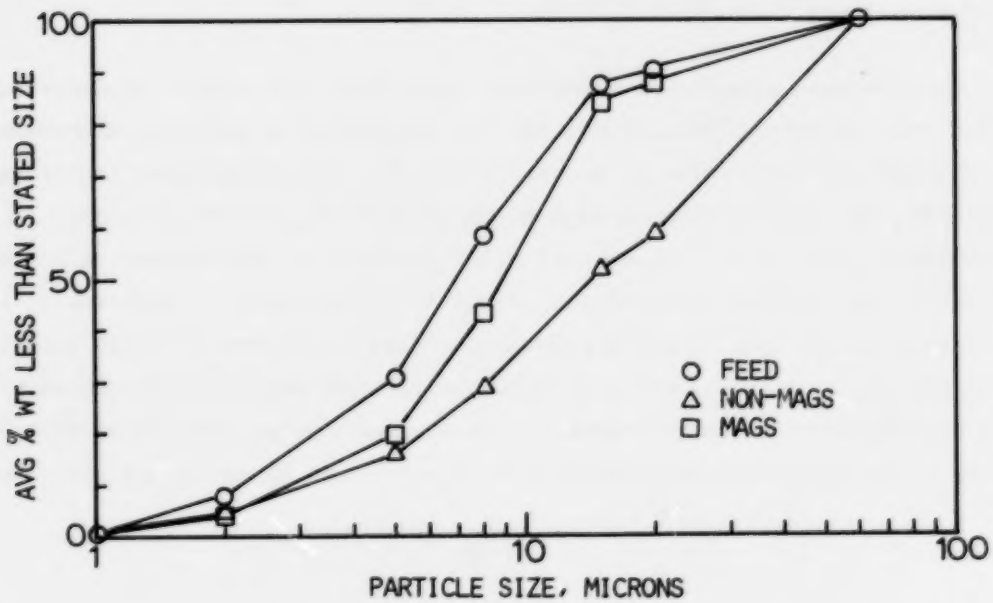



Figure 20. Magnetite particle size distribution. Same conditions as Fig. 19 except H = 3.0 kG. Mags represent 96.7% of the feed weight.

Figures 21 and 22 represent runs at 500 and 3000 gauss respectively. A dispersant was used in these runs and, like most of the coal-magnetite work, these samples were dumped through the matrix without first filling it with water. The effect of the dispersant is not evident at the low field. These curves are essentially identical with those in Fig. 19. Also, the mode of operation seems to make little difference.

At 3000 gauss, however, the difference (Figs. 20, 22) is striking. The relative position of the non-mags and mags distribution curve is reversed. In the latter experiment many more fine particles show up in the non-mags. The dispersant which may help prevent agglomeration of fines with larger particles and the more ordered flow seem to interfere with the trapping of the finer particles. An important point to be kept in mind is that the mags collection at 3000 gauss is at least 95% of the feed weight so the differences seen in these graphs may be entirely due to impurities in the magnetite rather than magnetite itself. The Davis Tube recovers only 91% of the magnetite and the HGMS collects only 95-96% of the feed magnetite even at 6000 gauss.

One more result may illuminate separately the effect of dispersant and mode of operation. In Fig. 23 the results of a run with dispersant but with filling the matrix beforehand are shown. In comparison to the results in Fig. 20 (without dispersant) there is a shift of fine particles to the non-mags (e.g., 22% < 5μ vs. 16% < 5μ) but not to the extreme of the results in Fig. 22 (unflooded operation, 30% < 5μ in non-mags). Apparently, both dispersant and the flow characteristics have an effect on fines collection. It may be, as we have noted above, that the non-mags consist entirely of much more weakly magnetic material than magnetite so that these effects are to be expected and the question of magnetite fines is not yet resolved.

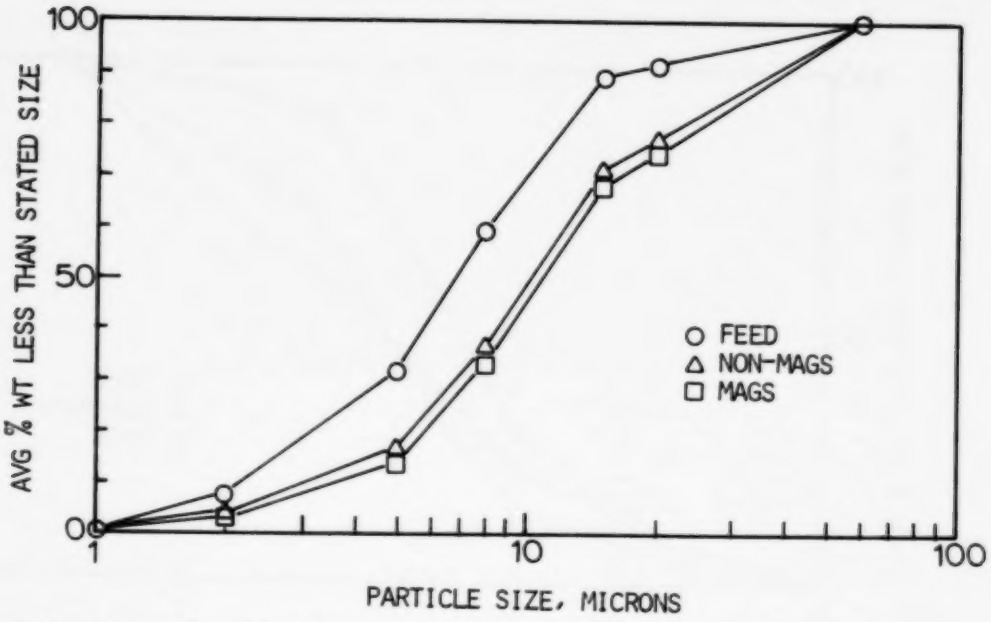



Figure 21. Magnetite particle size distribution with dispersant. All distributions were obtained using the HIAC Particle Size Analyzer. Matrix was not filled before run. H = 0.5 kG.

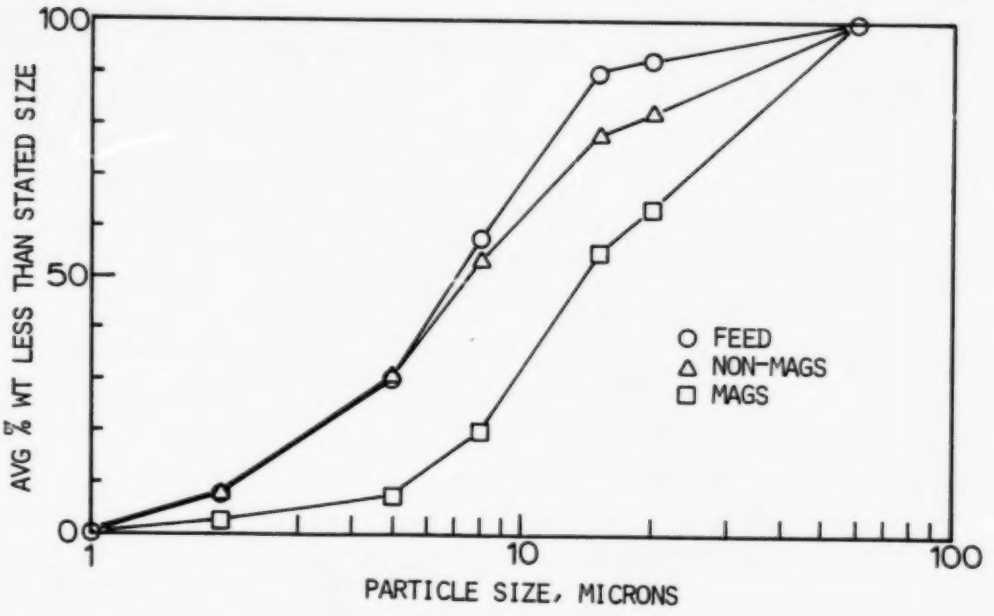



Figure 22. Particle size distribution for magnetite at 3.0 kG with dispersant. Matrix not filled before run.

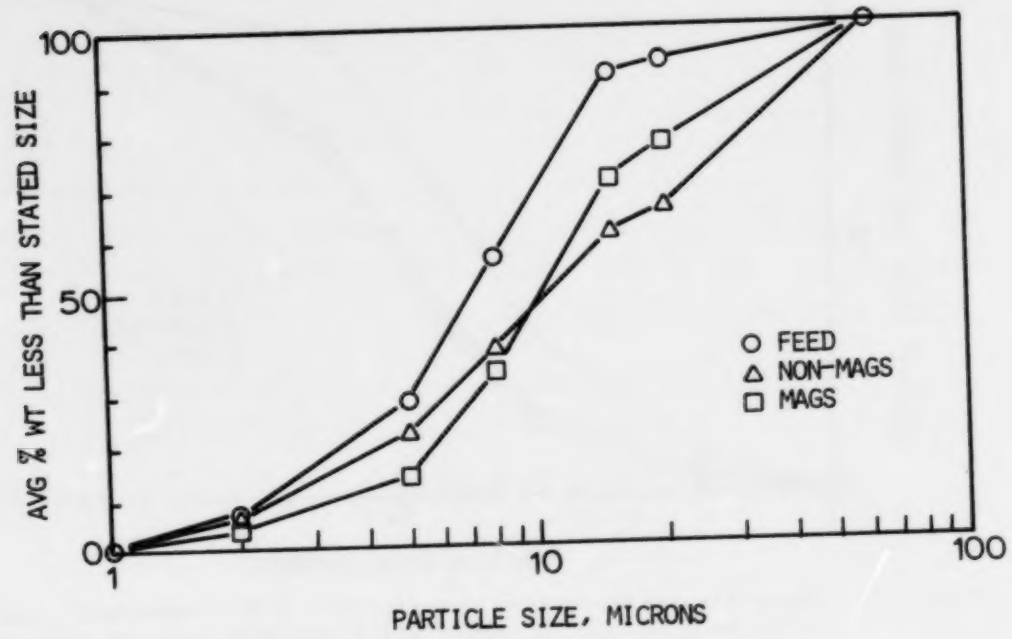



Figure 23. Magnetite particle size distribution at 3.0 kG with dispersant and matrix filled before the run.

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

The main result of this project was the separation of magnetite from coal using an experimental High Gradient Magnetic Separator which achieved high throughput rates, high values of magnetite recovery, and small amounts of coal reporting to the magnetics.

The throughput rates, calculated as weight of feed divided by the time to pass through the matrix, vary from 1 to 4.4 tph/$ft^2$. The actual rate of passage of feed material through the matrix is higher because we include some process water in this calculation. Much higher rates are possible than this and we plan to initiate work to explore higher throughput values.

The results quoted here for magnetite recovery (99.9% or higher at highest throughput values) are at least comparable to values claimed for drums and the value for coal reporting to the magnetics is probably lower. Magnetic field values of 6 kG were the highest used in this study.

A new matrix design proved successful at recovering fine grade magnetite, passing the coarser coal and allowing easy recovery of the magnetics. Washing off the magnetics was accomplished by passing water through the separator in the same direction as the slurry. In a typical set of runs, the feed time was 3.5 seconds for a rate of 15.6 gpm and the wash time was 2.5 seconds at a rate of 48 gpm. Most of the magnetite was removed in the first half of the wash time, but using these feed and wash times, the duty cycle for a batch separator would be 58% not counting switching. Continuous separators like one tested at M.I.T. on iron ore (with magnetics content similar to our samples in this project and at slurry densities up to 40% solids) might be used in place of batch separators.

We have seen that the use of a dispersant and the flow characteristics affect fines collection. Particle size analysis shows that magnetic agglomeration occurs and that HGMS is effective in fines collection as far as we have gone.

Recommendations

The flow rates used in this study have been such that a very substantial throughput has been achieved. However, improvements in this rate have not been explored and, as with loading, we do not know the limits of throughput. This is an important piece of information which should be obtained.

Among a number of tasks which need to be followed through, an important one is the question of how compact the matrix can be made to allow for reductions in the necessary magnetic field volume. Less field volume would mean lower magnet capital cost. The length of the matrix might be reduced without loss in efficiency of magnetite capture, and the matrix material and cross-sectional loading changed without increasing coal loss.

We have used one kind of stainless steel expanded metal and have not studied the effect of the use of other materials on fine particle capture. This clearly needs to be done, and done in conjunction with improvements in matrix design.

Since the matrix has never been loaded to its capacity, a further study of loading should be carried out to give an idea of the duty cycle required for a batch-type device.

Multiple passes have not been attempted in this study but could make possible more efficient collection of different size ranges of magnetite, possibly in part at lower field values, the use of which would reduce capital cost. Matrix materials should be studied as to their effectiveness on fine particle collection and different matrices might be used on successive passes, each tailored to the particle size and average magnetic moment in each size range.

Improvement is needed in the identification of impurities as they pass through the separator both to characterize the process and to study impurity build-up in a coal-cleaning circuit.

Flexibility in the application of HGMS to magnetite recovery in coal cleaning would be achieved by doing more work on the overflow and underflow

products from the heavy-medium cyclone including products from the cyclone when operated at varied values of specific gravity. Also, other coals or other samples of the same coal should be tested.

It would be helpful in future work to have a full coal analysis done. This was beyond the scope of this project but would help identify impurities and, if a BTU analysis were performed on the separator products and feed, one could know the real loss of what is important to a boiler operator.

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## APPENDIX I

### Ash Balances for Two Sets of Runs

| RUN | ASH WT. PROD. (gm) | ASH WT. MAGS (gm) | TOTAL ASH WT. | CLOSURE (%) |
|---|---|---|---|---|
| 116 | 19.76 | 146.03 | 165.79 | 100.3 |
| 118 | 14.46 | 152.23 | 166.69 | 100.8 |
| 120 | 100.32 | 65.81 | 166.13 | 100.5 |
| 121 | 35.86 | 129.74 | 165.60 | 100.1 |
| 122 | 17.98 | 146.80 | 164.78 | 99.6 |
| 123 | 19.23 | 149.18 | 168.41 | 101.8 |
| 124 | 17.56 | 149.65 | 167.21 | 101.1 |
| 125 | 13.55 | 148.51 | 162.06 | 97.99 |
| 126 | 12.68 | 152.13 | 164.81 | 99.66 |
| 155 | 95.04 | 70.85 | 165.89 | 100.3 |
| 156 | 66.32 | 100.21 | 166.53 | 100.7 |
| 157 | 32.42 | 134.87 | 167.29 | 101.2 |
| 158 | 17.71 | 148.99 | 166.70 | 100.8 |
| 160 | 16.15 | 150.75 | 166.90 | 100.9 |
| 161 | 16.40 | 150.31 | 166.71 | 100.8 |
| 162 | 9.92 | 150.56 | 160.48 | 97.04 |

Feed: Coal 13.0% Ash
Magnetite 102.4% Ash

For these runs wt. ash in Feed: 165.37 gm

## APPENDIX 2

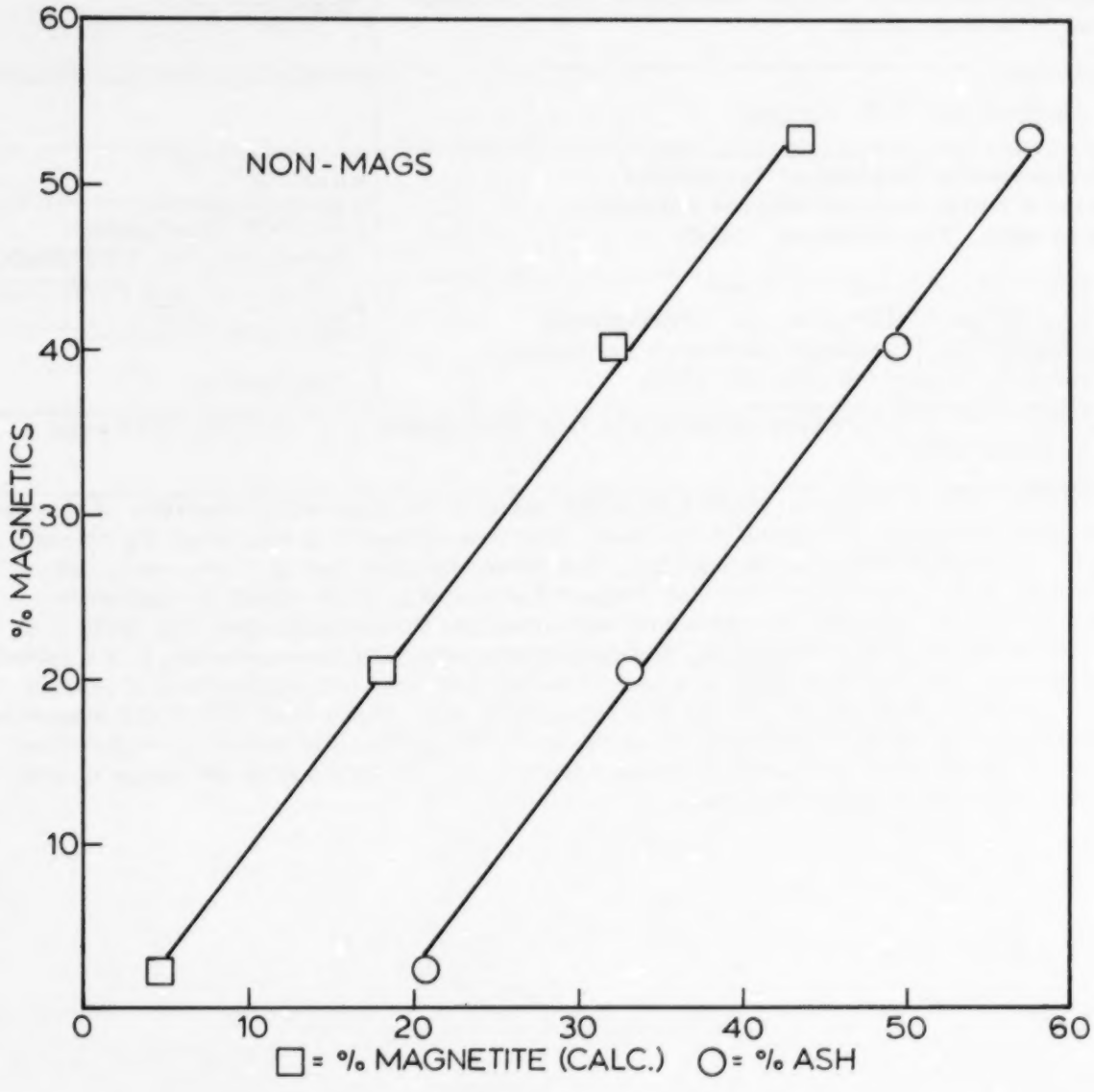
### Typical Iron Balances

| RUN | WT. FE (gm) PROD. | MAGS | TOTAL | CLOSURE % |
|---|---|---|---|---|
| 139 | 30.09 | 66.80 | 96.89 | 99.8 |
| 140 | 4.63 | 91.69 | 96.32 | 99.2 |
| 141 | 2.96 | 92.14 | 95.10 | 98.0 |
| 142 | 2.66 | 93.15 | 95.81 | 98.7 |
| 143 | 2.57 | 92.36 | 94.93 | 97.8 |
| 144 | 2.26 | 91.81 | 94.07 | 96.9 |
| 145 | 2.53 | 90.36 | 92.89 | 95.7 |

Feed: Coal 2.33% Fe
Magnetite 63.30% Fe

For these runs wt. Fe in Feed: 97.06 gms

APPENDIX 3




Appendix 3. Correlation between pairs of analyses for non-mags products of four runs, (155-158) for which field values range from 0.5 to 3.0 kG. The correlation coefficients (r) and 0.999 (□) and 0.999 (o). $\left(r = \frac{m^2 \sigma_x^2}{\sigma_y^2}\right)^{1/2}$ where m = slope and σ = standard deviation. For runs 120-122 the corresponding values of r would be 0.987 and 0.999. Using Davis Tube magnetics values in place of magnetometer measurements for these runs r = 0.976, 0.999 respectively.

**TECHNICAL REPORT DATA**
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15. SUPPLEMENTARY NOTES Project officers are D. A. Kirchgessner (EPA/IERL-RTP) and R. E. Hucko (DOE).

16. ABSTRACT The report describes a demonstration of the successful recovery of magnetite from mixtures of magnetite and coal, like those found in a coal-washing circuit, by High Gradient Magnetic Separation. The demonstration was part of a research program at Francis Bitter National Magnet Laboratory. High values of magnetite recovery were achieved at reasonably high material throughput rates with little coal found reporting to the magnetics. A single-stage separator incorporating a new matrix design was used at rates up to 4.4 tons of solids per hour per square foot of matrix cross section (300 gpm/sq ft). At this throughput rate, more than 99% of the magnetite was trapped along with less than 5% of the coal. Magnetic field values no higher than 6 kilogauss were used to achieve these results, a value well within the range of present commercial magnet designs.

17. KEY WORDS AND DOCUMENT ANALYSIS

| a. DESCRIPTORS | b. IDENTIFIERS/OPEN ENDED TERMS | c. COSATI Field/Group |
|---|---|---|
| Pollution<br>Coal Preparation<br>Magnetite<br>Magnetic Separators<br>Magnets<br>Magnetic Properties | Pollution Control<br>Stationary Sources<br>High Gradient Magnetic Separation | 13B<br>08I<br>10A<br>13I<br>20C |

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